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DETERMINATION OF THE MINIMUM USE LEVEL OF FUEL SYSTEM ICING INHIBITOR (FSII) IN JP-8 THAT WILL PROVIDE ADEQUATE ICING INHIBITION AND BIOSTATIC PROTECTION FOR AIR FORCE AIRCRAFT

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Interim Report

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UNITED STATES AIR FORCE

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14. ABSTRACT
Fuel System Icing Inhibitor (FSII) additive, a mandatory additive in JP-8, is used to prevent solidification of free water in the fuel and to provide protection against microbial growth in fuel systems. The current FSII additive approved for use is Di-Ethylene Glycol Monomethyl Ether (DiEGME). The fuel specifications require that JP-8 be procured with 0.10 to 0.15% by volume of FSII (MIL DTL 83133F) with an on-aircraft minimum use limit of 0.07% (USAF T.O. 42B-1-1). The objective of the current study was to determine if the required minimum use concentration of FSII in JP-8 can be reduced and still provide similar icing inhibition and biostatic capability as the current 0.07% requirement. A reduction in the required FSII concentration will result in significant fuel/logistical cost savings and could reduce the occurrence of FSII-related Fuel Tank Topcoat Peeling in certain aircraft fuel tanks. This report provides an overall summary of the experimental studies and analyses performed and the resulting recommendations. Results from the present effort indicated that a minimum use limit of 0.04% by volume of FSII will provide for safe operation under expected water levels and flight conditions for aircraft operating with JP-8. Biological growth studies indicated comparable bioefficacy to current requirement levels should be maintained.

15. SUBJECT TERMS
FSII, Aviation Fuel, JP-8, A/C Use Limit, Icing Inhibition, Bacteria, Microbial Contamination, B-52, Icing Rig, Aqueous Solution, Partitioning Coefficient, Solubility, Fuel Filter

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

PREFACE

This report was prepared by the Air Force Research Laboratory (AFRL), University of Dayton Research Institute (UDRI) and Encore Support Systems Limited Partnership under Subcontract 09-S590-0011-02-C2 with Universal Technology Corporation under Contract FA8650-08-D-2806 with AFRL/RQ. Mr. Charles Delaney was the Principal Investigator and team leader in support of Dr. Donald K. Phelps and Dr. James T. Edwards of the Fuels and Energy Branch (AFRL/RQTF), Turbine Engine Division, Aerospace Systems Directorate, Air Force Research laboratory (AFRL), Wright-Patterson, AFB, Ohio.

The technical lead for these studies was AFRL/RQTF with the primary technical effort being performed by UDRI under Cooperative Research Agreements F33615-03-2-2347 and FA8650-10-2934. Other team members are: the Air Force Petroleum Agency (AFPET); ASC/ENFA; the Universal Technology Corporation (UTC); Encore Support Systems LLP; OC-ALC/327 ACSG, Tinker AFB, OK; the Boeing Company; and the U.S. Navy (NAVAIR 4.4.5). The efforts herein were performed to determine the minimum required use limit of the Fuel System Icing Inhibitor (FSII) additive to maintain safe operability of USAF aircraft. Concurrent with the completion of these efforts, the AFPET determined the procurement limits and concentration range required to insure the minimum use limit is maintained at the aircraft. The AFPET had overall management responsibility for the program, as well as provided expertise relating to fuel properties and handling, planned and performed the in-field survey to determine the FSII losses in the fuel logistics and storage systems, and is responsible for coordinating and accomplishing any resulting changes to the JP-8 specification, handbooks, other fuel handling documentation, NATO Standard Agreements (STANAGs) and AISC Air Standards. OC-ALC/327 ACSG and the Boeing Company gathered information and provided AFRL with guidance relating to aircraft fuel systems and components vulnerable to freezing water in fuel and researched and provided guidance on the component-level icing tests. ASC/ENFA provided guidance to AFRL as well as coordinated the technical results of the program with the aircraft SG/OEM community. Encore Support Systems, formerly C4e, Inc., assisted AFRL and UDRI in the planning and performance of the research relating to the icing inhibition and biostatic capability of reduced DiEGME concentrations. The U.S. Navy provided guidance and technical advice on the experiments conducted to determine the minimum required FSII level in the fuel. The aircraft FSII use requirement determined by AFRL plus the additional FSII required due to the losses in the transportation/storage facilities during procurement by AFPET provided the basis for recent modifications in the use (T.O. 42B-1-1) and procurement specifications (MIL-DTL-83133H) for JP-8 fuel. This report describes the studies, analyses, and experiments that were performed to define the maximum quantity of water expected in the fuel of Air Force aircraft (JP-8) and the minimum concentration of Di-Ethylene Glycol Monomethyl Ether (DiEGME) required to prevent fuel system icing while providing comparable protection against biological growth to that for previous procurement and use levels.

1. Executive Summary

There is significant interest in determining the minimum on-board use concentration of the Fuel System Icing Inhibitor (FSII) additive required in U.S. military aviation fuel JP-8 that can provide for safe and reliable operation. Lower FSII concentrations will yield significant logistical and economic cost savings. In addition, undesirable material compatibility issues attributed to DiEGME could be reduced. Due to the complexity of independently determining a minimum use limit for each USAF aircraft, experimental studies and conservative analyses were performed to provide an aircraft-independent recommendation. The primary efforts performed herein include: estimation of the expected total water content on-board aircraft, the characterization of the partitioning of FSII from fuel to any free water present, and small- and large-scale icing studies. In addition, studies were performed to characterize the bio-efficacy and potential for reduced occurrence of Fuel Tank Topcoat Peeling (FTTP) with a lower FSII concentration in the base fuel.

Results from the present effort supported the feasibility of a reducing the use limit of FSII from the previous minimum (0.070% by volume) while maintaining safe operation of aircraft. Estimations and in-field measurements of the total water content expected on aircraft indicate that low quantities of water (< 120-130 ppm) should be encountered during standard operation. Partitioning measurements show FSII readily migrates from fuel into free water and the propensity and percentage of the migration increases with reduced temperature and concentration. Biological growth studies indicated that even at reduced levels of FSII in the base fuel, the resulting aqueous phase concentration will be sufficient to provide comparable performance to the previous use levels. Extensive small-scale icing studies with strainer filter elements used on B-52 aircraft and metal screens show that concentrations much lower than currently required can prevent ice formation of large water concentrations, even at the specification temperature limit of JP-8 (-47°C). Large-scale component testing performed with a B-52 strainer housing provided validation of the small-scale testing with improved definition of the required use limit. Overall, it was determined that <u>a minimum use limit of 0.04% FSII will provide for safe operation under expected water levels and flight conditions for aircraft operating with JP-8</u>. Biological growth studies indicated that even at this reduced FSII level in the base fuel, the resulting aqueous phase concentration should be sufficient to provide comparable performance to current FSII use and procurement levels. This lower concentration (0.04%) may reduce the frequency of Fuel Tank Topcoat Peeling occurrences. This document comprises a summary of the overall activities performed; a more-detailed final report will follow. Implications of FSII-loss during fuel transfer and storage were addressed in a separate effort by the Air Force Petroleum Agency (AFPET) to define the required FSII procurement range required to insure the minimum use limit is achieved at the aircraft. The loss-study showed that the majority (> 97%) of USAF bases surveyed had statistical losses of less than 0.02% FSII by volume through the procurement chain.

2. Introduction

The use of a Fuel System Icing Inhibitor (FSII) is required in JP-8 military aviation fuel per Specification MIL-DTL-83133H. The purpose of the FSII is to prevent any free water within the fuel from solidifying and preventing fuel flow to the aircraft engines. The FSII requirement was initiated in 1961 following several reported incidents which attributed fuel system malfunctions to ice formation (Langer, 1960; Martel, 1987). Di-Ethylene Glycol Monomethyl Ether (DiEGME) is the currently approved FSII additive in both JP-5 and JP-8 fuels. The structure of DiEGME is shown in Figure 1. The fuel specification and technical orders for JP-8 use were recently modified and require an on-board minimum FSII use limit of 0.040% by volume (USAF T.O. 42B-1-1) with a procurement range of 0.07-0.10% (MIL-DTL-83133H). The previously established use and procurement ranges (MIL-DTL-8333G) were 0.07% and 0.10-0.15%, respectively. The previous levels were in-use for numerous years and specified following studies which attempted to determine the minimum necessary FSII with an added level of safety for procurement losses (Martel, 1987; DeWitt et al., 2007). However, the majority of the studies were performed using the previously approved FSII, Ethylene Glycol Monomethyl Ether (EGME), in JP-4 fuel and applicability to the current fuel and FSII are unknown.

$$CH_3-O-CH_2-CH_2-O-CH_2-CH_2-OH$$
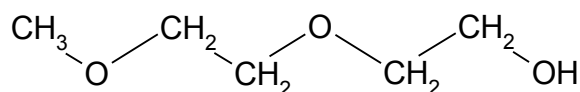
Figure 1. Structure of Di-Ethylene Glycol Monomethyl Ether (DiEGME).

There has been significant interest in determining the potential for reducing the required FSII dosage in JP-8. This interest is motivated by many factors, including both economic and operational reasons. There is a significant logistical and economic cost of incorporating FSII at high concentration, especially in forward-located operating positions. In addition, FSII has been implicated in the failure of integral Fuel Tank Topcoats (Aliband et al., 2006; Marlowe and Green, 2007; Zabarnick et al., 2007; Aliband et al., 2008; Zabarnick, 2010) and a reduced concentration in the fuel may alleviate the occurrence of failures. Many factors support the possibility for a lower FSII-use concentration while maintaining safe aircraft operation. These include significant improvements to fuel transfer and storage systems which reduce the levels of water contamination (i.e., FSII loss) and hardware modifications made to legacy aircraft to prevent water accumulation or ice formation. In addition, FSII is not required in commercial Jet A or Jet A-1 fuels, indicating the possibility for safe operation without the additive. However, there are significant differences in commercial operations that should be considered. Both Jet A and A-1 are approved as alternate or emergency fuels for most USAF aircraft, also supporting operation without a FSII. The U.S. Navy performed extensive small-scale and component-level testing which resulted in a minimum use limit of 0.030% by volume in JP-5 (per NAVAIR 00-80T-109). However, the Navy requirement only pertains to S-3, US-3 and SH-60 aircraft (paragraphs 9.5.4 and 15.5.4) while all other Navy and U.S. Marine Corp (USMC) aircraft do not require FSII and may use JP-5 or other approved fuel even if it does not contain the additive. However, minimum operation without FSII is recommended due to the potential lack of biostatic protection in aircraft and storage systems. The Federal Aviation Administration (FAA) issued an Advisory Circular (AC 20-29B) in 1972 regarding the use of the previously approved FSII

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(EGME (trade name of PFA-55MB)) in aviation kerosene. The advisory stated that data indicated that 0.015% by volume of FSII would prevent ice formation in fuel containing 100 ppm of water (by volume) to temperatures of -40°C; unfortunately, this data is not referenced. However, the minimum required use concentration was increased to 0.035% due to concerns with FSII loss during procurement, free water accumulation in aircraft fuel tanks, and measurement accuracy. A further recommendation was also made to refuel the aircraft with at least 0.060% as an additional level of safety.

It is difficult to solely use the aforementioned studies and analyses to specify a minimum use limit for all USAF aircraft due to varying complexity, fuel system design, and mission profiles. However, these do provide a strong basis for further evaluation and a guide for further study. Improved understanding of the manner by which FSII acts to prevent solidification of water under conditions pertinent to aircraft fuel systems will assist with determining the feasibility for safe operation with a lower use limit. Recently, extensive experimental studies and analyses were performed at the Air Force Research Laboratory which improved the basic understanding of the manner by which FSII functions and interacts with water in aviation fuel (DeWitt et al., 2005; DeWitt et al., 2005b). These efforts identified critical areas for further investigation which would assist in determination of a minimum FSII use concentration while maintaining safe operability of all USAF systems.

The USAF, with funding from Defense Supply Center Richmond, initiated an effort to expand on the preceding research and development efforts to attempt to determine the minimum required FSII use limit. The overall program had two primary goals:

1) Determination of the Minimum Use Limit On-Board USAF Aircraft
2) Determination of the Required Procurement Limits to Insure the Former is Obtained

The Fuels and Energy Branch of the Air Force Research Laboratory (AFRL/RQTF) was tasked with performing the requisite efforts for determination of the minimum use limit while the Science and Technology Division of the Air Force Petroleum Agency (AFPET/PTPT) performed a procurement-loss survey. This report will be limited to efforts and analyses related to determination of the required FSII level on-board the aircraft. Based on prior efforts, three primary areas for study were determined to assist in providing a quantitative basis for the minimum use limit on-board aircraft:

- Estimation of Representative Total Water Content in USAF Aircraft
- Measurement of Equilibrium Partitioning of FSII between fuel and water at Reduced Temperatures
- Icing Inhibition Evaluation
  o Small-Scale Icing Studies
  o Large-Scale/Component Icing Studies

Additional considerations include; reviewing the efficacy of a reduced FSII concentration as a biostat in aircraft storage and fuel systems, the potential of lower FSII concentrations in fuel to reduce the frequency of Fuel Tank Topcoat Peeling on DoD aircraft, and the extent of FSII loss in the fuel delivery and procurement chain. Detailed studies were performed related to these

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topics. This report will only include a top-level summary of primary conclusions from these efforts.

The experimental efforts and analyses were performed herein to provide a platform-independent basis for the evaluation of the minimum FSII use limit. However, the B-52 was used as the primary evaluation platform when necessary. The designation of the B-52 is justifiable for several reasons. The B-52 was the primary driving force for FSII development due to aircraft mishaps attributed to fuel system icing in the late 1950s. The aircraft mission profile is typically comprised of high altitude/long duration flights where the bulk fuel and wing surfaces can reach very low temperatures. The fuel system does not contain any specific hardware to prevent icing or water accumulation in the fuel transfer system. For example, the B-52 were previously equipped with fuel heaters (which used engine bleed air) in the engine struts between the fuel tank boost pumps and fuel strainer. The heaters were deactivated on H-model B-52s in 1962 (per Time Compliance Technical Order (TCTO) 1B-52H-606), removed from all B-52s except G-model in 1968 (per TCTO 1B-52H-663 and TCTO 1B-52-1878) and completely removed from G-models in 1969 (per TCTO 1B-52G-733). The aircraft does not have a water-scavenge system or On-Board Inert Gas Generation System (OBIGGS) to prevent accumulation of free water in the aircraft.

The purpose of this report is to provide an overall summary of the experimental studies performed and the resulting recommendations regarding the minimum on-board use limit of FSII while maintaining safe operability. This data was used to justify the recent reductions in the FSII use and procurement ranges in USAF JP-8 fuel. A more detailed final report will follow which will provide further data inclusion and discussion on each of these, and supplemental, activities performed.

3. Experimental Studies and Analysis

The following sections will provide an overview of the various primary research activities and analyses performed in this program and present the most significant results obtained. The final report for this program will provide expanded discussion and data inclusion on each of these efforts.

3.1 Estimation of Representative Total Water Content in USAF Aircraft

The determination of the "representative" and "worst-case" total water content expected on-board aircraft is critical for evaluations of FSII effectiveness since the required dosage is directly influenced by the total water in the fuel system. In addition, specification of these levels is critical when considering only a single mixing event between FSII-treated fuel and free water. Unfortunately, there is very limited data available regarding the expected water content within aircraft fuel tanks during operation. The majority of this information pertains to specifying the total water content for component and fuel system icing evaluations without the use of a FSII. Therefore, several parallel approaches were taken to determine appropriate total water content levels for subsequent FSII evaluations.

3.1.1 SAE Recommended Water Levels for Icing Studies

Aircraft components and fuel systems are subjected to icing qualification testing prior to certification for use in aircraft. The SAE Aerospace Recommended Practice (ARP) 1401B and Aerospace Information Report (AIR) 790C provide general guidance regarding the total water content and test conditions that should be used during icing studies. The recommended water levels are based on analyses and studies performed in the late 1950s-early 1960s. The initial recommendations were "combined" and documented in MIL-F-17874B (Fuel Systems: Aircraft Installation and Test of, 20 Aug 1965). However, the basis for the recommended water levels is unclear. The ARP and AIR detail three basic testing regimes with recommended total water content. All test regimes require that the fuel be conditioned and saturated with water at 80°F and filtered with a coalescer, which results in a dissolved (and total) water content of approximately 90 ppm (by volume). The three test regimes with total water content and general comments are:

1. **Continuous System Operation**— Water-saturated fuel resulting in a minimum total water content of approximately *90 ppm*, with an acceptable range of *90 – 130 ppm* for testing. This is intended to simulate the "cruise" portion of the flight cycle, when the aircraft fuel system is subjected to cold temperatures with water saturated fuel and no excess water. This level of water has been used as an industry standard for icing studies.

2. **Emergency System Operation**— Water-saturated fuel + 198 ppm free water (*288 ppm total*). This is a short duration test (< 30 min) to simulate the effect of the presence of excess water in the system and verification that the fuel system can still supply adequate fuel flow for engines being powered up for an "emergency," such as a go around maneuver.

3. **Filter Bypass Function Operation**—Water-saturated fuel + 528 ppm free water (*618 ppm total*). This is a very specific test condition with the purpose to demonstrate functional capability of the bypass feature of a filter element or specific component when subjected to ice blockage. This condition was referred to as "Component Testing" in the previous version of the ARP (SAE ARP 1401A).

For evaluation of a FSII effectiveness to prevent blockage due to icing, the **Filter Bypass Function Operation** regime is excessively high and not representative of typical expected water content on aircraft. In the event that this level is achieved, either a significant failure in fuel handling would have occurred or standard aircraft practices (e.g., sumping) would not have been followed. For the latter, the free water would have been exposed to repeated volumes of fuel and achieved equilibrium with FSII providing a limited degree of safety.

Based on the limited available information, it could be acceptable to use the **Emergency System Operation** water content (≤ 288 ppm) as an "upper water limit," which has been implemented for previous small-scale FSII evaluations. However, this level is much higher than typically accepted for the standard (**Continuous System Operation)** operating level of ~90 ppm and only used for short-duration evaluations. Therefore, it is believed that the typical total water content of fuel is ≤ 90 ppm and this level could be reasonable for evaluations of reduced FSII concentration. However, this level may not be indicative of an acceptable "worst-case" water content. Due to the lack of detailed guidance for evaluation of a FSII and the inability to obtain documented reports of the technical studies from which the basis for these water levels were made, efforts were undertaken to provide an improved basis for the total water content for use in this study. Specifically, calculations were performed to estimate the expected water levels within aircraft due to fuel tank breathing (Section 3.1.2) and extended in-field sump sampling measurements were performed (Section 3.1.3).

3.1.2 Calculated Water Introduction During Aircraft Breathing
Fuel can be exposed to water contamination at various points within the procurement, logistics and storage chain, but the fuel must be filtered twice prior to introduction to the aircraft as per T.O. 42B-1-1. For currently approved filter coalescer elements (API 1581, Edition 5), this T.O. also specifies that fuel entering the aircraft can contain dissolved water with a maximum of 10 ppm free water. This is more stringent the API 1581 specification which allows up to 15 ppm free water. Therefore, based on the solubility of water in aviation fuel, it would be expected that the worst-case water content of the fuel will initially be ≤ ~90 ppm (as discussed above). However, the dissolved water content will most likely be significantly lower than the corresponding solubility limit, especially when fuel handling and storage facilities are well-maintained. Once the fuel is on-board the aircraft, the only viable mechanism for water to enter the aircraft is by condensation of water vapor during fuel tank "breathing." This can occur for vented tanks either on-ground due to daily temperature/pressure cycles or during flight due to pressure/temperature and fuel volume changes with altitude and flight time. Accordingly, calculations were performed to estimate the magnitude of water that could be introduced during breathing. A similar effort has been described briefly in the literature, but the data is not readily available (Oreshenkov, 2004). It should be noted that water could also be introduced during aerial refueling. However, it is expected that the aerial refueler (e.g., KC-135) would have

comparable water and FSII contents resulting in minimal impact on the total water content following fuel transfer.

3.1.2.1 Calculated Water Introduction During Ground-Based Breathing
Detailed calculations were performed to investigate the potential for water introduction due to <u>ground-based breathing</u>. For these calculations, the total fuel and ullage volumes, temperature, pressure, initial water content of the fuel and relative humidity (RH) of the ullage vapor and external air must be specified (e.g., initial conditions). Specific assumptions made during calculations were:

- Constant fuel and ullage volumes
- Vapor behaves as an ideal gas
- 1-Directional transfer of water from vapor to liquid
- Ideal mixing of liquid
- Tank ullage equilibrates with external pressure
  - Vent system does not contain valve which requires cracking pressure to allow air exchange
- Fuel components do not volatilize
- Steady-state conditions during each calculation

These calculations attempted to model the exchange of gas volume between the ullage and external atmosphere that occurs via pressure fluctuations in the ullage due to daily temperature changes. Two basic events for air exchange are either an increase or decrease in temperature. For the **<u>increase in temperature</u>** case:

- Local temperature and pressure within ullage increases
  - Initial total moles of gas (vapor) calculated via ideal gas law; ullage volume is constant
- Vapor is vented from tank
  - Total vapor moles in ullage decreases, pressure equilibrates with external atmosphere
- "New" relative humidity within ullage is calculated based on saturation pressure of water ($p^*_{sat}H_2O$) at elevated temperature and total moles of water

For the increase in temperature case, it can be observed that (1) water vapor should not condense, (2) vapor will be expelled from the ullage space, and (3) the relative humidity will decrease since the temperature rises and water in the fuel is not permitted to re-enter the ullage.

For the **<u>decrease in temperature</u>** case:

- Local temperature and pressure within ullage decreases
- Water vapor in ullage can condense:
  - Calculate maximum water content in vapor at new temperature based on p*satH2O
  - **For calculation, all water vapor above the saturation pressure (at specified temperature) is assumed to condense (e.g., 100% efficiency) into fuel**
  - New water content in fuel is calculated
  - Loss of water vapor due to condensation will result in further decrease in "local" ullage pressure

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- Vapor enters ullage from external atmosphere to equilibrate pressure with atmospheric conditions
  o Total moles of vapor entering are calculated based on total ullage volume and ideal gas law
  o Properties of vapor entering (e.g., relative humidity, temperature) are specified
- New "effective" properties of vapor in ullage (i.e., relative humidity) are calculated

For the decrease in temperature case, it can be observed that (1) vapor will be drawn into the ullage space from the external atmosphere, (2) water vapor can condense and enter the fuel if the initial conditions render greater than 100% RH at the final ullage temperature, (3) if water condenses, the final RH in the ullage is 100%, and (4) final properties of the ullage space are calculated using the final temperature and pressure, initial ullage properties, moles of water vapor that condense, and the mass and properties of external air drawn into fuel tank.

Various calculations were performed using the methodology above to estimate the quantity of water that would enter the fuel during consecutive ground-based temperature excursions (e.g., day/night cycles) where the temperature varies cyclically. The aircraft was assumed to be filled with 50% fuel volume as a conservative case. For structural and mission preparedness reasons, aircraft are fueled with a "ramp load" shortly after returning from a mission and the fuel tanks do not remain empty for any significant length of time. Several specific cases were performed where the day/night temperatures ranged from 100-110°F and 60-70°F, respectively, while the external air was assumed to always remain at 100% RH (most likely a conservative overestimation). The air initially in the ullage was assumed to be at the highest temperature with an initial relative humidity (RH) from 50-100%. As will be shown below, the specification of the initial temperature and RH in the ullage most strongly affects the total water introduction into the fuel tanks. Calculations were performed for consecutive day/night cycles where a single cycle consisted of the temperature varying from the high-to-low temperature and back. Since the assumptions and methodology used require steady-state calculations, these were performed using sequential temperature increments of 10°F. The incremental water addition as a function of the calculation step and corresponding temperature for a case with day/night temperatures of 110°F and 60°F and an initial RH in the ullage of 100% is shown in Figure 2. It can be observed that the majority of the condensed water vapor enters the fuel during the first cooling event (approximately 52 ppm total), but minimal water enters during subsequent cycles (~1 ppm). The magnitude of the initial water introduction is highly dependent on the initial RH and temperature in the ullage. After the initial condensation, there is minimal water introduction although the calculations show that the air exchange mass percentage is approximately 9% of the ullage during the subsequent cycles. Although this appears to be a relatively high mass exchange, the corresponding water concentration is sufficiently low to not result in a significant amount of total water intake. To further illustrate the effect of the initial RH of the aircraft ullage and the temperature range, additional calculations were performed and are shown in Table 1. As shown, the magnitude of the initial water condensation is highly dependent on the initial ullage conditions, but there is still minimal water introduction in following cycles although the external air always remains at 100% RH.
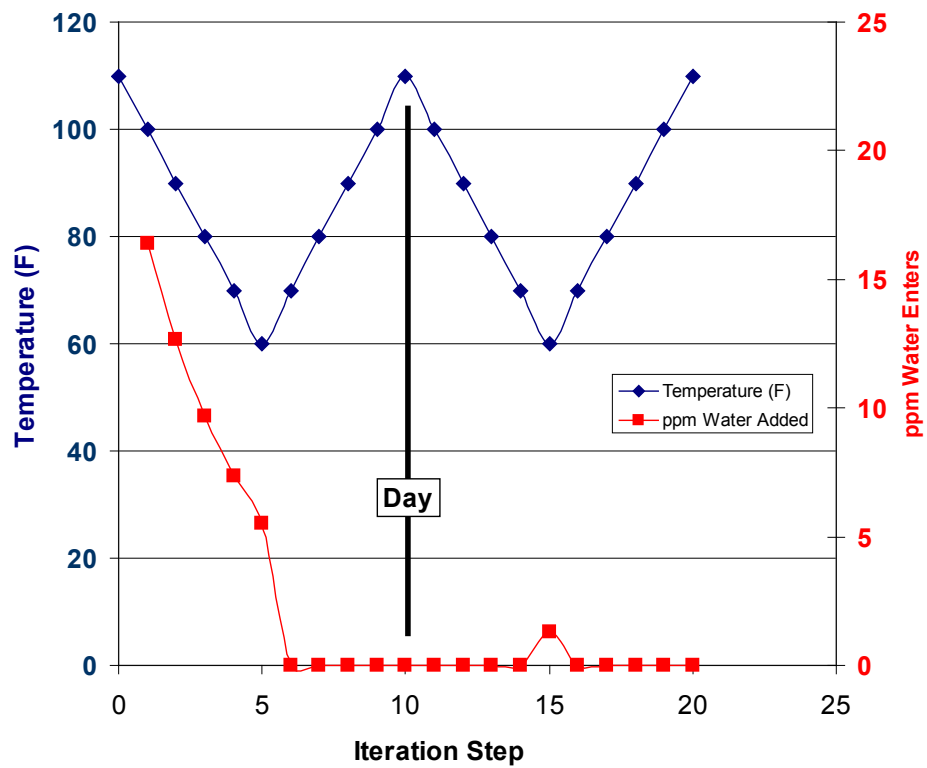
Figure 2. Calculated Incremental Water Addition during Ground-Based Breathing for an Aircraft Tank with 50% Ullage Volume as a Function of the Iteration Step and Corresponding Temperature.

9

Table 1. Calculated Water Introduction during Ground-Based Breathing for Aircraft Tank with 50% Fuel Volume and Varying Temperature and Initial Ullage Conditions

Temperature Range (°F)	Initial RH in Ullage (%)	Initial Water Added (ppm)	Water Added per Following Cycle (ppm)
60-110	100	52	1
	75	36	1
	50	20	1
60-100	100	35	1
	75	23	1
	50	11	1
70-110	100	46	1
	75	30	1
	50	14	1
70-100	100	30	1
	75	18	1
	50	6	1

Overall, the ground-based breathing calculations demonstrate that minimal water should be introduced following the initial "condensation event". Even if this initial water introduction is significant, this water should settle and be removed during subsequent sumping which should maintain a low total water content. Typically, technical specifications require that the aircraft be sumped prior to take-off which should remove most accumulated water. It is possible that substantial water introduction, settling and removal could also result in loss of FSII from the fuel. The extent of FSII loss will be based on the volume percent of free water and the partitioning behavior, which will be discussed in Section 3.2. Overall, these analyses indicate that the amount of water introduction due to ground-based breathing should be relatively low, especially after an initial condensation event. Even if the fuel is completely water-saturated during refueling (~80 ppm), it appears a maximum extreme case of ~130 ppm would occur.

3.1.2.2 Calculated Water Introduction During Flight
Calculations were performed to estimate the extent of water introduction during flight. Similar assumptions to those made for the ground-based breathing were used. The major difference is that the transient dependence of the temperatures for the condensing surfaces and bulk fuel had to be specified. These heat transfer calculations are very difficult to perform numerically as they are dependent on numerous variables, including (but not limited to): ambient air temperature, wing geometry, effective heat transfer coefficient across the air boundary layer, and the aircraft velocity (affects aerodynamic heating). The first assumption used herein was that the time-scale for heat transfer (i.e., temperature change) is much longer than that for the aircraft climb/descent. The consequence of this assumption during aircraft ascent is that the air will be expelled from the ullage due to a reduction in atmospheric pressure while the internal surface and fuel temperatures remain constant. During flight at altitude, the assumption is that the aircraft is operating for

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sufficient time for the surface and ullage gas temperatures to reach a final low value. During descent, external air is drawn into the aircraft while the surface and fuel temperatures remain at a low value. Moisture in the vapor phase can condense on the cold aircraft and fuel surfaces. A final calculation is performed on the ground allowing all temperatures to reach equilibrium with ambient conditions.

During these flight calculations, it is necessary to specify the pertinent atmospheric conditions as a function of altitude. For simplification, the pressure and temperature as a function of altitude were estimated using the NASA Earth Atmosphere Model (NASA, 2007). The model assumes that pressure and temperature change only with altitude, based on the effect of air density on absolute pressure. The corresponding relationships for temperature and pressure as a function of altitude for the troposphere (altitude < 11,000 m) are:

$$T(°C) \ = \ 15.04 - 0.00649 * height(m)$$

$$P(kPa) = 101.29 * \left[\frac{T + 273.1}{288.08} \right]^{5.256}$$

Based on the assumptions and methodology described, the amount of water that would enter the bulk fuel during a flight was estimated for a conservative case. For the calculations discussed below, the flight cycle consisted of an initial ground temperature of 90°F (32.2°C), climb to a horizontal cruise at 10,000 m (32,800 ft), and a rapid descent to ground. The fuel tank was assumed to be comprised of 25% fuel and 75% ullage. For simplicity the fuel level did not vary since the calculations were time-independent. The RH was assumed to be 100% for all altitudes, including initially in the ullage; this assumption was made to be conservative. Due to the assumption that the time scale for heat transfer was much longer than for altitude change, the calculations were performed with respect to 500 meter step changes in altitude. Once at altitude, the condensing surface was allowed to decrease step-wise to a final temperature (-40°C for this calculation) followed by the ullage temperature. The calculated amount of water entering the fuel as a function of the iteration step is shown in Figure 3. The corresponding altitude is shown for reference. Water does not enter the fuel during climb due to the decrease in air pressure (e.g., air expelled from ullage) and the assumption that the condensing surfaces temperatures do not decrease until cruise altitude is reached. Once at altitude, water condenses due to the decrease in surface temperature (Iteration Steps 21-23). Since the ullage is assumed to be homogeneous and any moisture content above the water saturation vapor pressure of the surface temperature condenses, essentially all water vapor remaining in the ullage enters the fuel once the surface temperature reaches the specified minimum of -40°C ($p^*_{sat}H_2O$(-40°C) = 0.142 mmHg). During descent, air which can contain moisture is drawn into the aircraft; any water content above 0.142 mmHg will condense since the condensing surface temperature remains at -40°C. This leads to the slow increase in fuel tank water levels. The apparent spike after landing (iteration step 47) occurs since the temperatures are allowed to re-equilibrate at the ambient temperature (high moisture content) with a cold condensing surface. The overall quantity of water entering for this conservative calculation was ~42 ppm. This value may appear low based on the assumptions used, but insight can be provided by considering how the saturation pressure of water varies with temperature, and hence altitude. Once the aircraft is above ~ 5,000 m, the moisture content of the external air is extremely low (~1 mmHg) even if the RH is 100%. As a result, a significant

percentage of the air mass (> 35%) that is ultimately drawn into the aircraft during descent contains very low quantities of water. These calculations did not account for liquid water (e.g., cloud) that could be drawn in during descent, but this should occur only during a brief part of the flight at a low rate.

The amount of water entering during flight is strongly related to the initial fuel and ullage volumes used. For example, increasing the relative ullage volume increases the total mass of air which can be exchanged while decreasing the total fuel volume available (increase relative concentration of condensed water in fuel). Additional calculations were performed to evaluate the impact of these. The calculations showed that the water entering for the cases of initially 90% and 20% ullage volumes were 125 and 3 ppm, respectively. The 90% ullage volume calculation shows potentially a large water increase, but it should be noted that this is an extreme case and the water content would be significantly decreased via dilution upon refueling. For example, if the fuel initially contains 50 ppm total water, following flight the total water content would be 175 ppm. In the event the aircraft is refueled to a 50% ramp load with ground fuel containing 50 ppm total water, the resulting water content will only be 75 ppm. Overall, these calculations imply that only low quantities of water are drawn into the aircraft during a single flight cycle, significantly below that used for **Emergency System Operation** icing studies. If the required sumping T.O.s and maintenance practices are followed, water which enters the fuel system should not accumulate to a sufficiently high concentration.
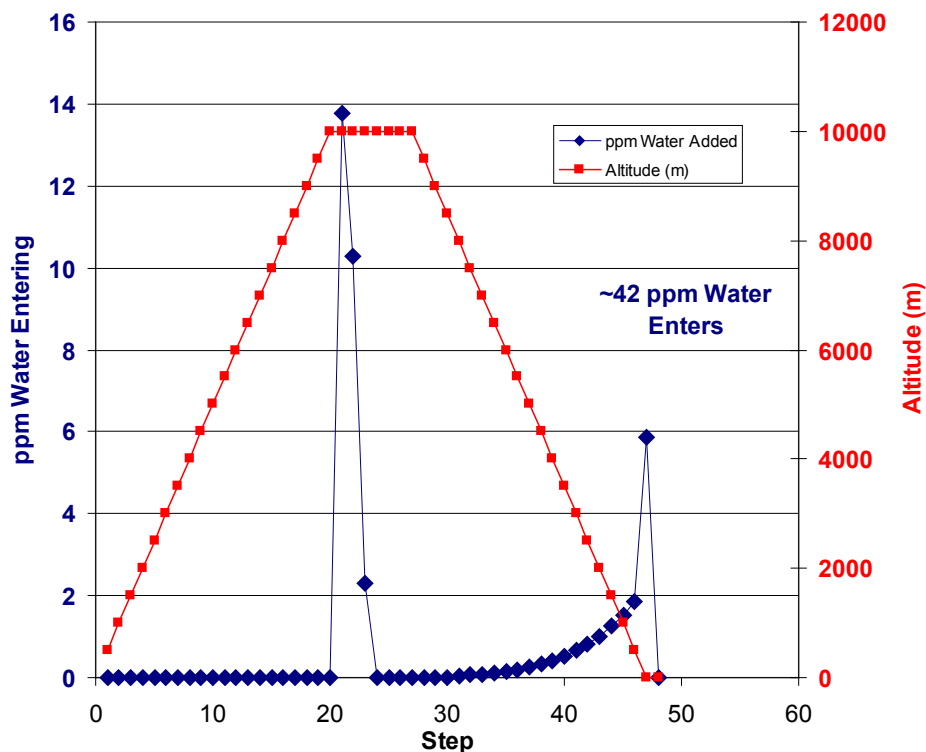

Figure 3. Calculated Incremental Water Addition during In-Flight Breathing with 75% Ullage Volume as a Function of the Calculation Step and Assumptions Used; Altitude Shown for Reference.

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3.1.3 Water Accumulation Study on Bomber-Type Aircraft
An extended in-field sumping effort was performed to attempt to investigate actual water accumulation in active bomber-type aircraft. The primary goal was to record the occurrences and quantities of free water collected during aircraft sumping, which would be indicative of the total water quantity introduced during aircraft breathing, both on the ground or during flight. The specific measurements of interest during each sumping were the total aqueous volume collected, the FSII concentration in the fuel and aqueous samples collected, and the total fuel volume in each tank. Aircraft types were selected which had vented fuel tanks and were not equipped with OBIGGS. Basing locations which had hot/wet climates were selected as the magnitude of water introduction due to fuel tank breathing would be intensified.

Separate sumping efforts were initiated at two locations (1 and 2) on two different types of aircraft (A and B). Two individual aircraft A were sampled at location 1 from July-September 2006, while A and B aircraft based at location 2 were sampled from April-September 2007 and October 2007 to February 2008, respectively. During this extended study, all fuel tanks were sumped per the requirements in the respective Technical Orders. During the sampling duration, there were extended periods of aircraft time on the ground with varying durations between flights. It is believed that sump samples were continually collected throughout the duration of this effort. A summary of the sump data for each aircraft type and location were combined and are shown in Table 2. As shown, there was a very low frequency of free water collected during this sumping activity. There was typically no free water collected during sumping; when water was observed it was relatively low volume ($< \sim 25$ mL total). These volumes corresponded to a very low concentration of free water in the fuel tanks (typically < 10 ppm). The DiEGME concentration in the fuel samples were all within the previous procurement range (0.10-0.15%) with the exception of 12 individual sump samples of 0.09% (3% of samples), indicating very little FSII loss due to water scavenging (and low free water content). These occurrences may potentially be attributed to the reproducibility ($\pm 0.018\%$) of the FSII quantification method used (ASTM D5006). The aqueous phase concentration was within the range expected for partitioning at ambient conditions and the fuel concentration (discussed in Section 3.2). It should be noted that there may be locations within the aircraft fuel tanks where water can accumulate but is not removed during sumping. The frequency and possibility of this type of occurrence will depend on the specific aircraft design.

Overall, the sumping efforts provided valuable data and insight regarding the introduction of water into aircraft fuel systems. The low occurrences of free water observed imply that:

1) Fuel handling and filtering efficiently remove free water from fuel during aircraft fueling.
2) The potential for free water accumulation in these aircraft is low provided that sumping is performed per the requirements in the respective T.O.s.

In addition, if an aircraft has specific hardware to prevent fuel tank breathing (OBIGGS) or accumulation of free water (water-scavenge rakes), there should be a further reduction in the potential for free water in the fuel systems. It should be noted that the potential for free water accumulation may increase significantly if proper fuel handling and filtering requirements or sumping intervals per the respective T.O.s are not strictly followed.

Table 2. Results from In-Field Sump Sampling of Bomber-Type Aircraft

Location	Aircraft	Dates	Total Aircraft Sumpings	Total Samples	Samples Containing Free Water	[DiEGME]$_{Aq}$	[DiEGME]$_{Fuel}$	Average Total Water (mL)
1	A	Jul-Sept 06	13	190	10 (*5.3%*)	~30-50%	0.09-0.15% Ave=0.12%	< 25
2	A	Apr-Sept 07	16	240	7 (*2.9%*)	~35-43%	0.09-0.14% Ave=0.12%	< 30
2	B	Oct 07-Feb 08	14	112	0	n/a	0.09-0.15% Ave=0.13%	n/a

3.1.4 Proposed Total Water Content for FSII Evaluations

Overall, the ground and flight-based calculations and in-field sumping measurements indicate that very low free water content should be expected during typical operating conditions provided required maintenance and sumping requirements are followed. In the event that free water does accumulate in the aircraft fuel tanks, the required pre-flight sumping should prevent accumulation of large quantities of free water. Therefore, it is reasonable to assume that for the majority of applications and missions, the total water content should be < 120-130 ppm total water if the fuel is water saturated and a high extent of aircraft breathing occurs. This is a conservative estimate as fuel entering the aircraft is most likely not completely saturated with water. This total water content is greater than that recommended for **Continuous System Operation** testing, providing an additional degree of conservativeness during evaluation of the efficacy of reduced FSII concentrations.

3.2 Measurement of Equilibrium Partitioning of FSII between Fuel and Water at Reduced Temperatures

Determination of the extent by which DiEGME partitions from the fuel to the aqueous phase at sub-ambient temperatures is useful because it can provide guidance regarding the freeze point suppression that can be obtained. The measured freeze point of DiEGME/water mixtures as a function of concentration is shown in Figure 4. At low FSII concentrations, the freeze point suppression is minor, but rapidly improves as the DiEGME concentration increases above approximately 50%. Since the specification fuel freeze points for JP-5 and JP-8 are -46°C and -47°C, respectively, there should not be icing concerns once the freeze point of the FSII/water mixture is below this value. In fact, this would provide for safe operability regardless of platform or mission profile. Since FSII is dosed into the fuel and must partition into any aqueous phase present, determination of the extent by which DiEGME migrates from the fuel to the aqueous phase is extremely important. This information not only provides a measure of the "potential protection" during flight (via freeze point depression) and a minimum required treat rate, but an estimate of potential FSII losses during fuel procurement and transfer can also be obtained.
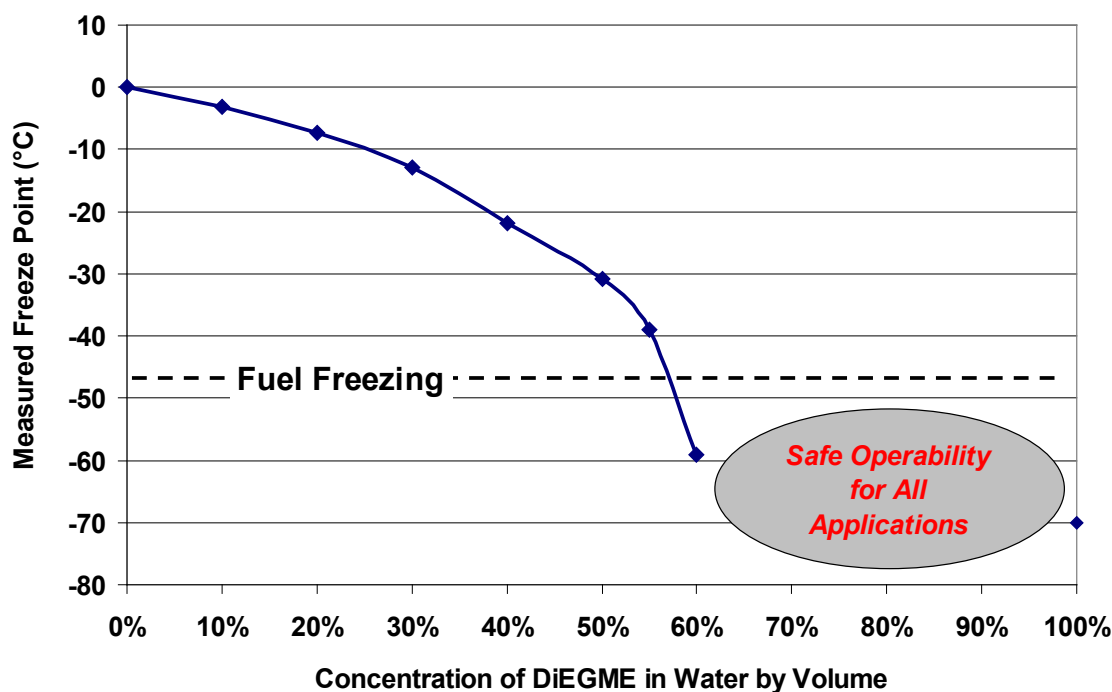

Figure 4. Comparison of Measured Freeze Point as a Function of DiEGME Concentration in Water (by volume) using Differential Scanning Calorimetry or ASTM D1177.

A measure of the migration of DiEGME between the fuel and aqueous phases in a closed system (e.g., fuel tank) can be expressed by the Partition Coefficient (PC):

$$Partition\ Coefficient\ (PC) = \frac{[DiEGME]_{aq}}{[DiEGME]_{fuel}}$$

where $[DiEGME]_{aq}$ and $[DiEGME]_{fuel}$ are the equilibrium FSII concentrations in the aqueous and

15
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fuel phases, respectively. A desired characteristic of FSII is that it is soluble in the base fuel but readily partitions into any water (e.g., has a high PC value). With respect to application, a high PC value will lower the initial FSII concentration in the fuel required to achieve a specific aqueous concentration. The functionality of the PC for a FSII/water/fuel system may be affected by both relative volume ratios and temperature.

There is very limited data available pertaining to the value and functional dependence of the PC for aircraft applications. In addition, the majority of the studies were performed for the previously approved FSII (EGME) in JP-4 fuels (West et al., 2014). Few studies have measured the PC of DiEGME in current aviation fuels, and all have been made at room temperature using DiEGME/water ratios of one or less with a total water concentration much higher than expected in the fuel. A ratio of DiEGME/water in excess of one will most likely be required to inhibit solidification of the free water at reduced temperatures (see Figure 4). Significant variance of the PC as a function of the DiEGME/water ratio, total volumes of FSII and water, or temperature could result in a large over- or underestimation of the required FSII treat rate.

An experimental system, termed the Sub-Ambient Liquid Equilibrium Measurement System (SALEMS), was developed to measure the partition coefficient under conditions representative of typical aircraft operation; a schematic of the SALEMS is shown in Figure 5. A detailed description of the system design and operation can be found elsewhere (West et al., 2014). This system employs a two liter Teflon separatory funnel in which the fuel/water/additive mixtures are placed. The separatory funnel allows very low water concentrations to be sampled, while the Teflon surface inhibits water adhesion. The temperature of the mixture is controlled within ±1°C inside an environmental chamber. A unique fluid ejector system is used to provide mixing during the cool down (-5°C/hr) period with the goal of avoiding loss of volatiles. 1.50 liters of fuel (unadditized Jet A-1) is equilibrated with the desired water and FSII levels for a period of at least three hours at the final test temperature. Thermocouples in the aqueous and fuel phases are used to confirm temperature equilibration. Two 1/16 inch O.D. capillary tubes are employed for sampling of the aqueous and fuel phases after temperature equilibration. Final DiEGME concentrations in the aqueous phase are determined using a digital refractometer (Reichert AR200) and in the fuel phase by gas chromatography/mass selective detection (GC-MS). During testing, the FSII concentration was varied from 0.01-0.15% by volume, the temperature from ambient to -47°C, and total water contents of 130, 220 and 560 ppm were used. It is believed that these experimental conditions encompass those expected during actual aircraft operation. Use of lower water contents (< 130 ppm) was not feasible as it was not possible to obtain sufficient aqueous volumes for analysis.
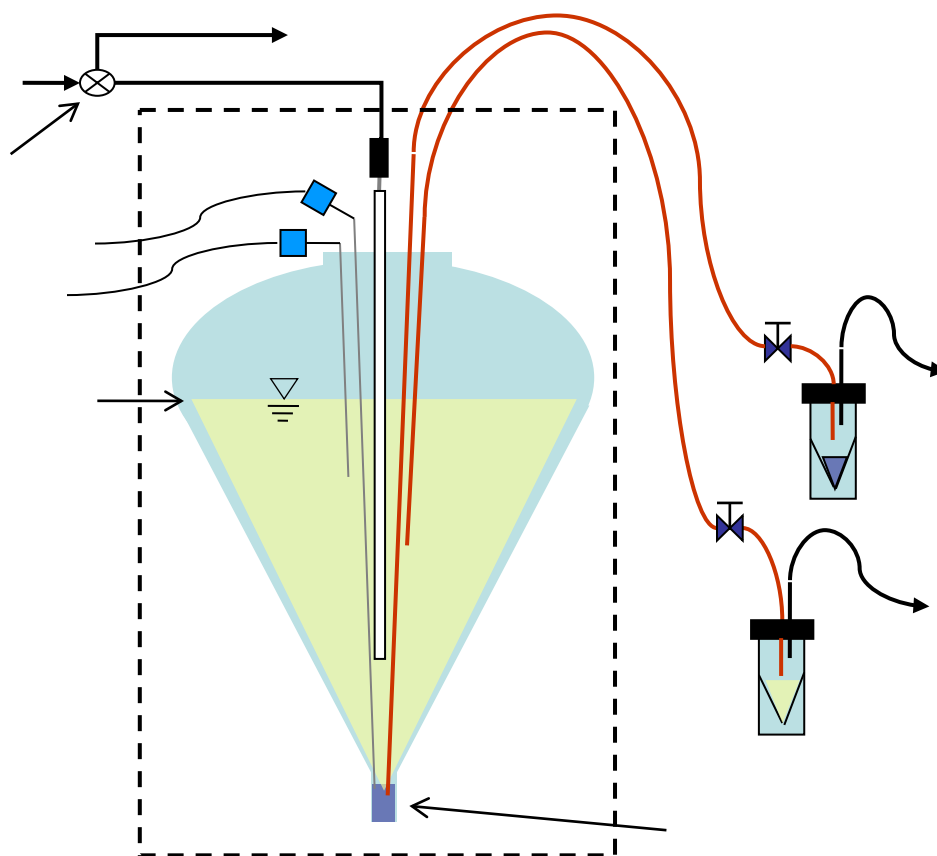
Figure 5. Schematic of SALEMS Apparatus, Dashed Line indicates Environmental Chamber Boundary.

The measured PC as a function of the equilibrium concentration of DiEGME in the fuel and temperature for all experimental conditions is shown in Figure 6. It can be observed that the PC significantly increases with both decreasing temperature and FSII concentration (i.e., FSII preferentially migrates from fuel to free water). The PC increases by a factor of ~4 at the lowest concentrations evaluated as the temperature is decreased from ambient to -47°C, supporting the reduction of the required FSII dosage. From an application perspective, the experimental data can be reviewed via comparison of the equilibrium aqueous and fuel phase concentrations as a function of temperature, as shown in Figure 7. This allows for direct estimation of the thermodynamic freeze point suppression via comparison of the equilibrium aqueous phase concentration to the corresponding freeze point curve (see Figure 4). A significant observation from this study is that for a specific temperature, there is a single equilibrium curve which is independent of initial fuel and water concentrations in the fuel (e.g., all data points collapse to distinct curve for each temperature). Therefore, the correlations shown in Figures 6 and 7 represent the corresponding equilibrium concentration in the aqueous phase when there is either: (1) a corresponding "final" concentration of DiEGME in the fuel following mixing or (2) a volume of water has been contacted with successive volumes of fuel treated at the specific DiEGME concentration. For a single-mixing event, the equilibrium fuel and aqueous concentrations achieved are dependent on the initial FSII and water concentrations, respectively, and determined by the overall mass balance.
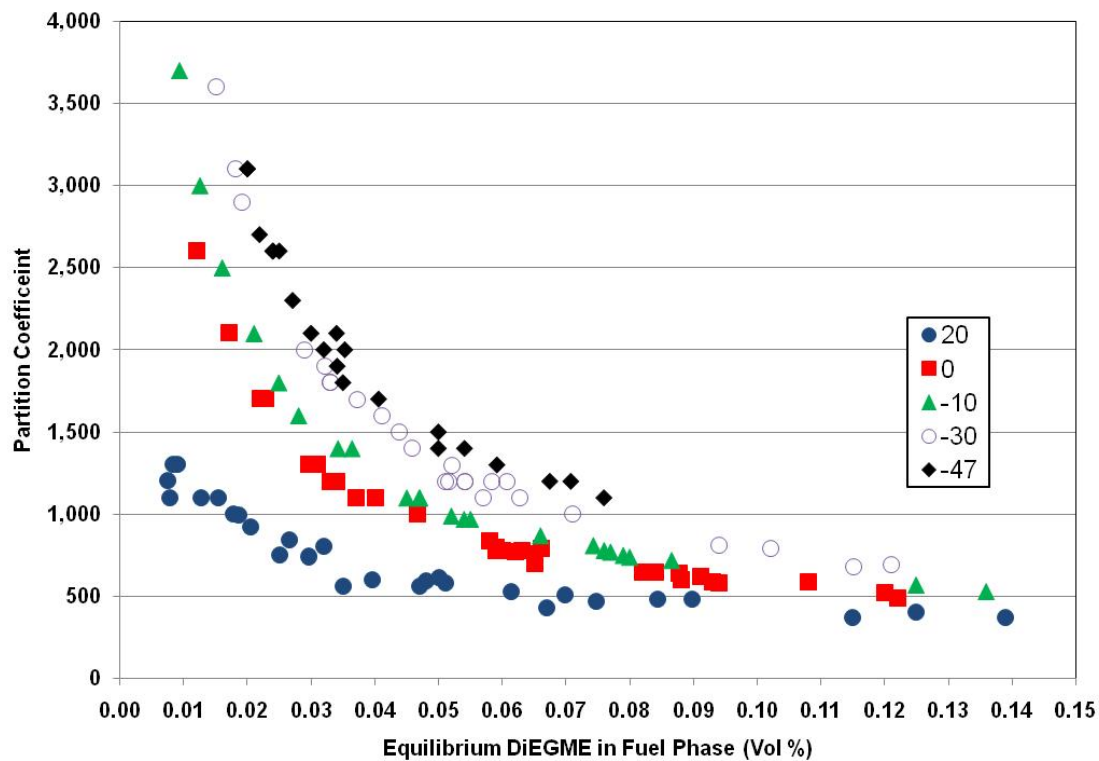
Figure 6. Measured Partition Coefficient as a Function of the Equilibrium Concentration of DiEGME in Fuel and Temperature (°C).
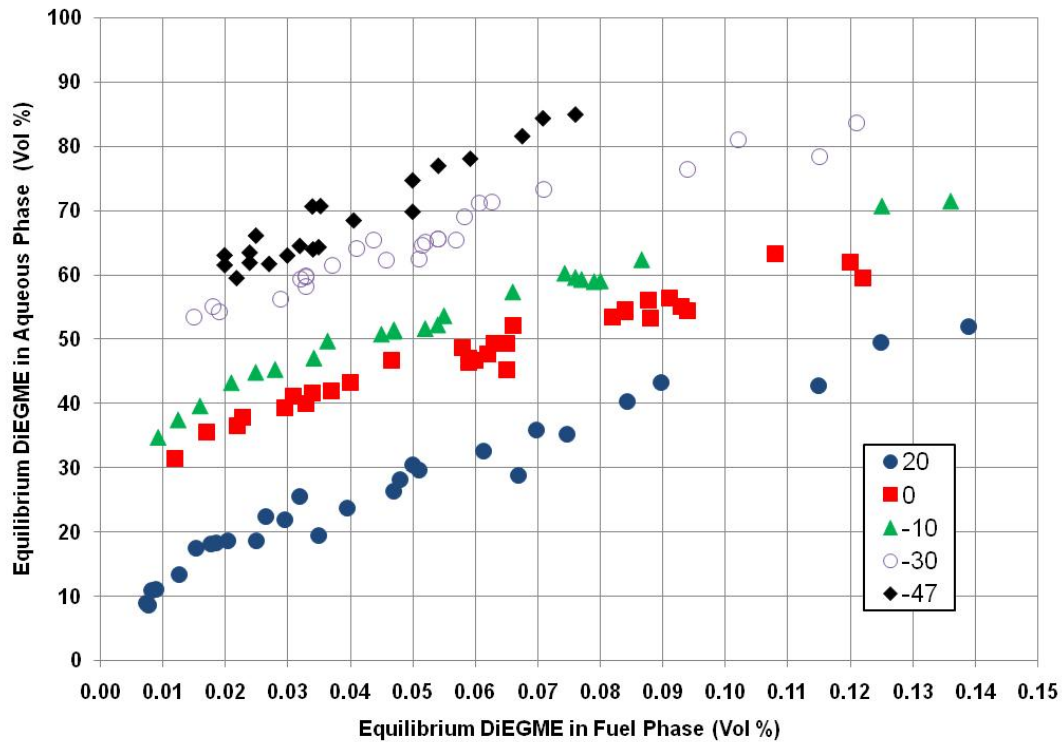

Figure 7. Relationship between Equilibrium Concentrations of DiEGME in Aqueous and Fuel Phases as a Function of Temperature (°C).

The partitioning data provides significant guidance regarding the expected FSII concentrations in any free water during application. For ambient temperatures and the previous procurement FSII range (0.10-0.15%), it can be observed that the measured aqueous phase concentration was ~35-50%, which is consistent with that typically reported in the field and also observed during the sump sampling efforts (Section 3.1.3). As the fuel concentration decreases, there is a corresponding decrease in the aqueous phase concentration. This could potentially reduce the extent of FSII-loss during procurement and fuel storage. As the fuel temperature decreases, there is a significant increase in the corresponding FSII concentration in the aqueous phase. A very encouraging result is that at FSII concentrations as low as 0.02% in the fuel, the equilibrium aqueous phase concentration should have a freeze point below that required for the fuel (-47°C) as the temperature is reduced. This behavior indicates that regardless of operational factors or platform, safe operability is probable provided there is adequate mixing and contacting during the cool-down of the fuel system. It should be reiterated that the experimental methodology employed herein only evaluates FSII partitioning at equilibrium conditions, thus determining the maximum aqueous phase concentration that can be achieved (since FSII migrates from fuel to free water). Dynamic and time-dependent effects, such as extent of mixing and diffusion, may affect the FSII in water concentration achieved during use and lead to a reduction in anti-freeze effectiveness.

3.3 Biostat/Biocide Activity at Reduced DiEGME Concentration

An important function of FSII, which is not part of the specification requirements, is the role as a biostat/biocide within bulk storage and aircraft fuel systems. It is believed that DiEGME can act to inhibit growth of bio-organisms and films which cause detrimental effects to fuel system operation. A potential concern with a reduced FSII concentration is that this bio-functionality would be reduced. Previous studies have demonstrated that for selected laboratory organisms, aqueous phase concentrations of FSII as low as 10-15% would still provide adequate protection against biological growth (Hill et al., 2005). As a part of the overall program investigating the potential reduction in the required use and procurement concentrations of FSII, additional detailed laboratory studies have been performed by the Biological Contamination Fuels Group of AFRL/RQTF and UDRI investigating the effectiveness of reduced DiEGME concentrations to inhibit growth of organisms commonly found in fuel. The organisms studied included laboratory organism strains from the American Tissue Culture Collection (ATCC): Pseudomonas Aeruginosa (Bacteria), Candida Tropicalis (Yeast) and Cladosporium Resinae (Fungus), and a mixed consortia of field organisms obtained during previous in-field aircraft sumping. A detailed summary of the experimental efforts and results are provided in a separate report (Balster et al., 2010). For the ATCC consortia, results comparable to the aforementioned study by Hill and colleagues were found where levels of DiEGME ≥ 10-15% were sufficient to prevent growth of the corresponding organisms. However, testing with the field consortia showed that DiEGME could not completely prevent growth, even at levels as high as 60% in the aqueous phase, but performance was similar for concentrations greater than ~20%. With respect to a reduced concentration of DiEGME in the fuel, the equilibrium levels in the aqueous phase will still remain at levels ≥ 20% even with fuel concentrations as low as 0.02% (see Figure 7). Therefore, the combination of the expected total water content in fuel storage system and aircraft, the equilibrium partitioning behavior, and the biological growth studies indicate that at least comparable performance to current procurement and use levels of DiEGME should still be realized with reduced concentrations of DiEGME in the base fuel.

3.4 Evaluation of Icing Inhibition in a Flowing Environment

Determination of the effectiveness of a FSII to provide for safe operability of a fuel system is difficult because there are no defined performance requirements to provide a basis of evaluation. With respect to specifying the required FSII use concentration, the determination is further complicated since the lower concentration must display comparable icing inhibition characteristics to previous fuel levels under realistic aircraft conditions. Icing studies for qualification of fuel system components are typically performed without FSII addition using the recommended total water levels discussed in Section 3.1.1. Performance evaluation for system operation is not standardized and strategies for evaluation are typically developed on a system or component-specific basis. Ideally, icing evaluations would be applicable to all aircraft; however, the wide variety of platform designs and mission profiles make this difficult. Therefore, it is desirable to investigate the FSII effectiveness at a reduced-scale as a function of the pertinent variables in a flowing system, which include temperature, total FSII and water content, screen type and flow passage size. This testing can provide information regarding the function of DiEGME under flowing conditions, which could possibly identify limitations not exhibited by static systems (e.g., equilibrium partitioning). This approach allows for numerous studies to be performed rapidly and to determine the critical operational regimes for FSII effectiveness. This information could then be used to guide large-scale evaluation of actual fuel system component(s) at a reduced FSII dosage.

3.4.1 Small-Scale Icing Studies

An experimental system, termed the Small-Scale Icing Simulator (SSIS), was developed to evaluate FSII effectiveness under the dynamic effects of water freezing in a flowing fuel line. The design has many similarities to the U.S. Navy Fuel System Icing Simulator (Cummings, 1997; Mushrush et al., 1999). A general schematic of the SSIS is shown in Figure 8. 9.5 liters of fuel is continuously recirculated at 0.5-2.0 L/min while the system temperature is slowly decreased by means of heat exchangers and an environmental chamber. The total water and additive concentration is specified prior to cooling. The system is designed to allow for interchangeable "test sections," which are located within the environmental chamber, to be readily evaluated. Blockage due to icing is evaluated by monitoring the pressure drop and flow rate across the test section. When ice begins to block the filter, the differential pressure drop increases sharply and the flow rate decreases, thus indicating a freezing event. Thermocouples are positioned throughout the system to monitor fluid temperatures at various points of interest. Testing is typically initiated without FSII and the failure temperature is measured. The system is returned to ambient temperature, and DiEGME is added (typically in 0.005% increments) for sequential evaluation of the FSII effectiveness.
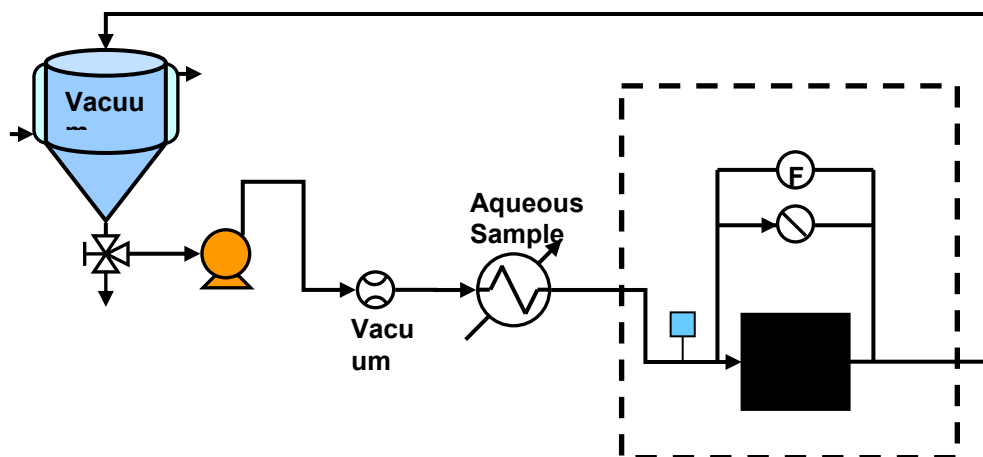
Figure 8. Schematic of the Small-Scale Icing Simulator.

Icing studies have been conducted using varying screen types and sizes. Testing is typically performed with total water concentrations of 288 and 600 ppm. These concentrations are much higher than those expected on aircraft, but provide very conservative estimates of the FSII effectiveness. Limited testing at lower concentrations has shown that only very low (< 0.01%) quantities of DiEGME are required to prevent icing. The majority of the studies have been performed using a custom-designed circular filter housing with a 1.59 cm diameter cross section (1.98 cm^2 area). Results from testing conducted using a cross-section of the cellulose filter used in the fuel strainer of the B-52 (nominal openings of ~ 40-50 μm) and a 50-mesh metal screen (320 μm square openings with 200 μm wire size) are shown in Figure 9. A total flow rate of 1.0 L/min with a cooling rate of < 0.5°C/minute was used during these tests. These experiments were initiated with 288 ppm water in Jet A-1 with sequential addition of FSII. Once the FSII concentration was sufficient that a failure was not observed, as indicated by a temperature value of -45°C, the total water concentration was increased to 600 ppm. As shown, much lower concentrations of DiEGME than previously required prevented icing failure. In addition, as expected, the required concentration decreases with the coarse filter. Reproducibility experiments were performed using the B-52 fuel strainer element; data for testing with 288 ppm total water are shown in Figure 10. As shown, there are slight differences in the DiEGME effectiveness curves due to experimental variability. This data is generally consistent with previous small-scale testing by the U.S. Navy using the Fuel System Icing Simulator with a target of 250 ppm total water, which is shown in Figure 11 (Cummings, 1997) Testing from both systems indicates that even with high concentrations of water, concentrations of DiEGME < 0.05% are effective at preventing solidification and blockage of the respective flow passages; indicating there is a strong potential for safe operation with FSII concentrations significantly lower than 0.07%. It should be noted that this type of recirculating testing is different from most typical aircraft which have a single-pass of the fuel followed by combustion. Additional testing has been performed to investigate the effect of alternate filter types, flow passage sizes, overall flow rate and total filtration surface area (affects linear fluid velocity) on FSII effectiveness. The data trends observed have been similar to those reported herein; results and discussion from those studies will be included in subsequent reporting.

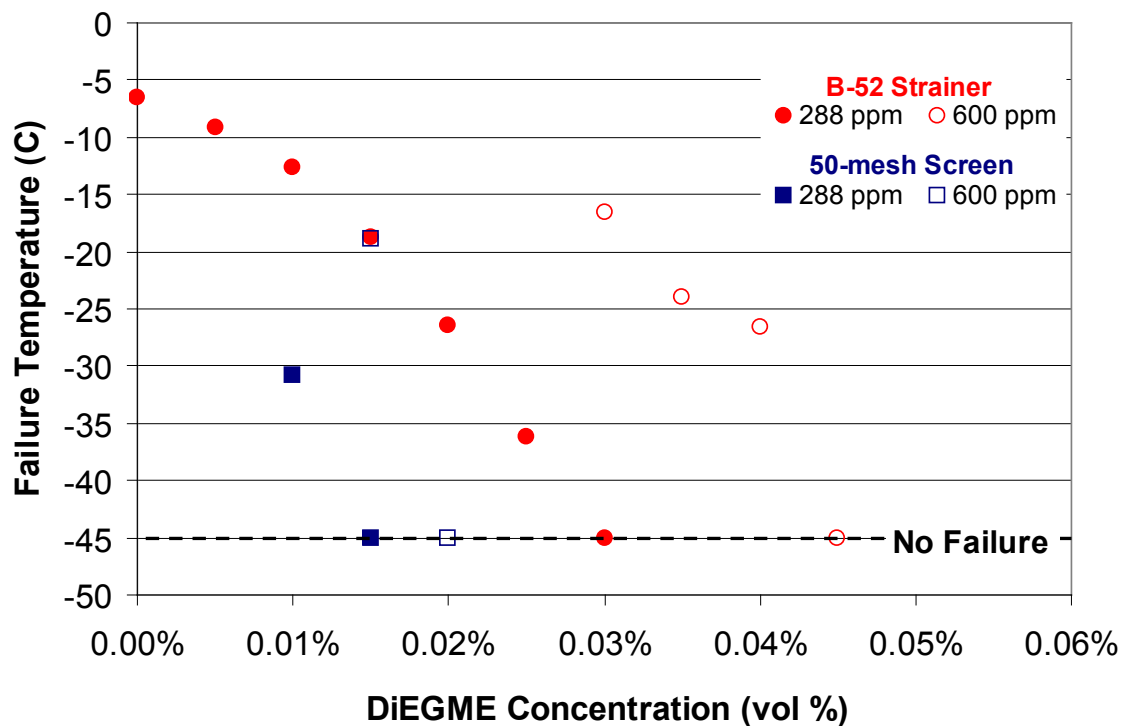Approved for public release; distribution unlimited.

Figure 9. Failure Temperature as a Function of DiEGME and Total Water Concentration for Testing with a Cross-Section of a B-52 Fuel Strainer Element and a 50-Mesh Screen.
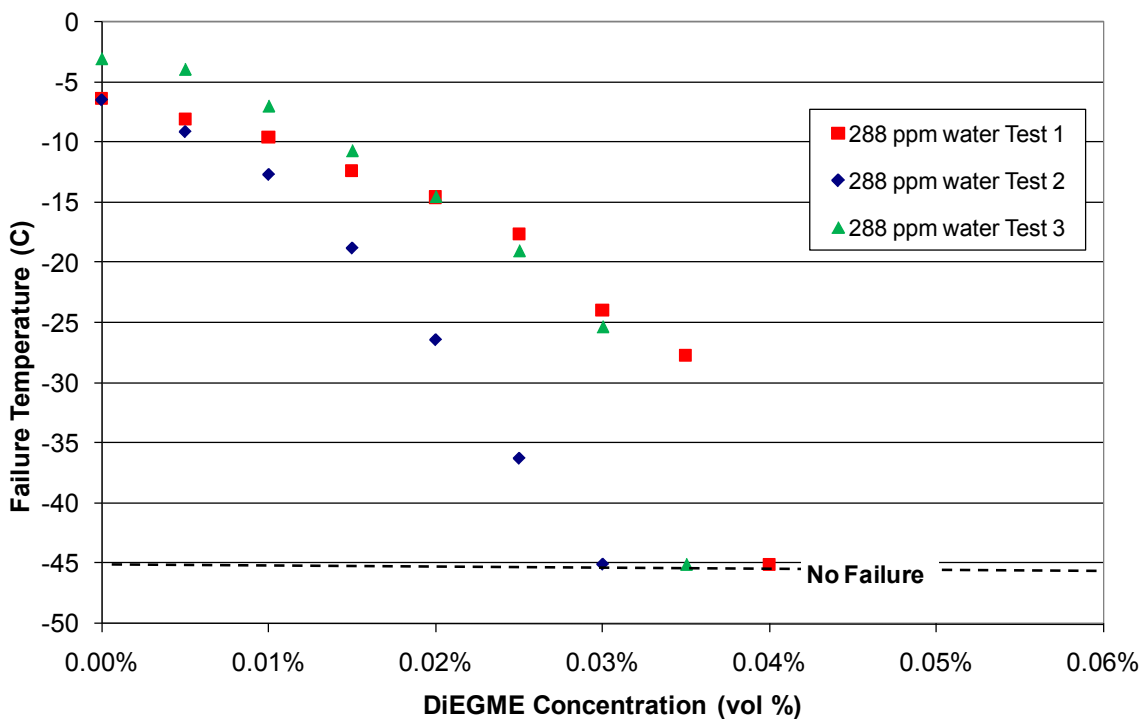

Figure 10. Failure Temperature as a Function of DiEGME Concentration for Testing with 288 ppm Total Water and a Cross-Section of a B-52 Fuel Strainer Element.

23

DiEGME Performance Graphs (Data taken 21 Jun 93 to 21 Jul 94; 27 Mar 95 to 9 May 96)
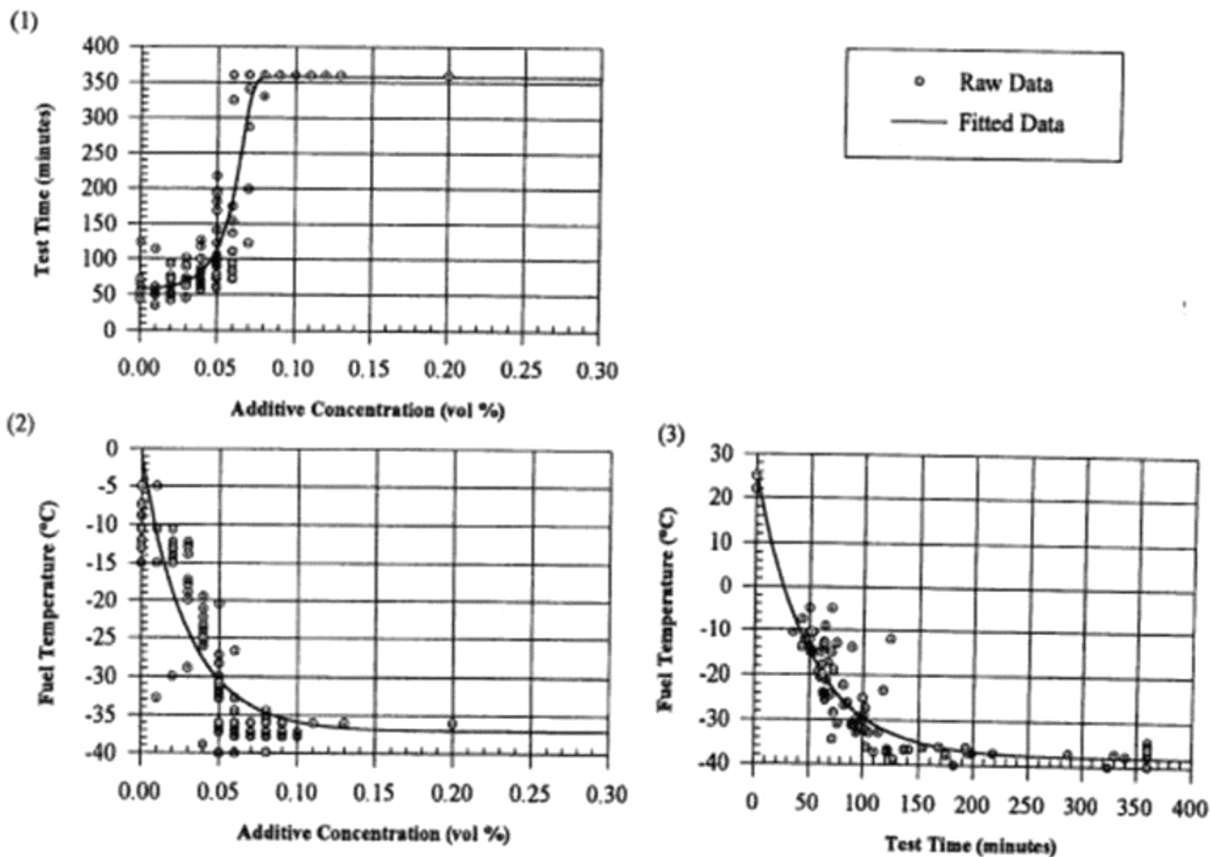

Figure 11. DiEGME Performance Data from Testing on U.S. Navy Fuel System Icing Simulator
(FSIS) with 250 ppm Total Water (Cummings, 1997).

3.4.2 Large-Scale Icing Studies

Large-scale evaluation of the effectiveness of a reduced DiEGME concentration is warranted as
it will validate the results from the static and small-scale flow testing under potentially more
realistic conditions. Ideally, a detailed review of all USAF platforms would be performed and
available which would identify both components prone to blockage due to icing and relevant
conditions (e.g., temperatures, flow rates) experienced. The U.S. Navy performed a survey of
various platforms which resulted in the identification of the SH-60, AV-8 and S-3 (and US-3
derivative) as having potential concerns with icing. Detailed review of these systems identified
the SH-60 foot valve, SH-60 fuel filter and US-3 motive flow, transfer ejector pump as critical
components for testing. The Navy performed large-scale component level testing with these
components, which indicated that addition of 0.03% FSII to JP-5 will allow for satisfactory
operation with a total water content of 100 ppm at -33.9°C (Tyler, 1988) For the current
program, similar information regarding a detailed review of all USAF platforms with
corresponding components and conditions potentially prone to icing concerns was not available.
Therefore, the approach was implemented to perform the evaluation on a platform/component
which could represent a "worst-case" operational condition, would provide a conservative

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estimate of reduced FSII efficacy, and be applicable to other platforms. As discussed in the Introduction, the B-52 aircraft fuel system was used for this basis for several reasons. The B-52 was the original driving force for the FSII requirement as aircraft crashes in the 1950s were attributed to excessive ice build-up in the fuel system. The B-52 typically has high-altitude/long-duration missions and large volumes of fuel, which can result in low fuel temperatures. There are no specific hardware within the fuel tanks and fuel transfer system to prevent water accumulation (e.g., water scavenge rakes or OBIGGS) or solidification (e.g., fuel heaters).

An independent effort was performed by Boeing and the B-52 Flight/Mechanical Systems Office to review the B-52 fuel system for locations and conditions that were most prone to icing vulnerability during operation. Several components in the fuel system upstream of the engines were identified for potential icing concern. However, it was determined that the fuel strainer housing between the main fuel boost pumps and the engine-driven fuel pump would be most prone to blockage due to ice formation. The fuel strainer is the first fine-flow passage after the fuel is transferred from the fuel tanks and is not actively heated. Therefore, it is rational to use this component for evaluation of a reduced FSII effectiveness since proper operation of this component will indicate that down-stream problems would be improbable. A schematic of the strainer housing is shown in Figure 12. During standard operation, the housing has a built-in bypass which can allow flow if the pressure drop across the filter element becomes too high. This could allow ice particles to flow to downstream components during standard operation. It should be noted that this component has passed icing qualification during FSII-free testing, most likely due to the bypass actuation.
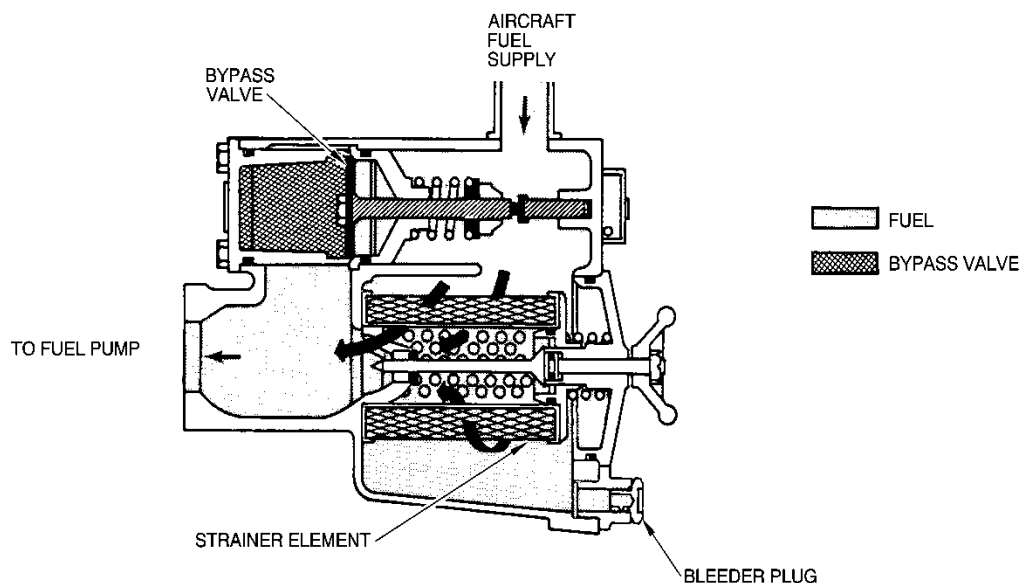

Figure 12. Schematic of B-52 Fuel Strainer Housing.

The evaluation of reduced FSII effectiveness was performed using a modified B-52 strainer housing; the internal bypass valve was wired shut to prevent opening during testing. The primary goal during testing with the B-52 strainer was to identify the minimum FSII concentration which would provide for safe operation without any appreciable solid ice

25

formation. Performing this testing with fuel conditioned with precise quantities of total water and FSII was critical to provide a valid basis for evaluation. In addition, testing under a representative fuel flow rate, temperature and duration were required. These overall constraints required that a large-volume of conditioned fuel and appropriate test facilities be available for the evaluation. It was determined that the testing would be performed by Parker Aerospace, Irvine California; Parker Aerospace has extensive test facilities and experience performing large-scale icing studies. A process flow diagram of the fuel conditioning and test system at the Parker Facilities is shown in Figure 13. The basic test methodology is comprised of pre-conditioning the test fuel to the water saturation limit at 80°F (per SAE ARP and AIR discussed in Section 3.1.1) via continuous recirculation of the condition tank through the fluid chiller followed by removal of excess water via the coalescer (Filter/Water Separator in Figure 13). Once achieved, the required additional water volume and FSII are sequentially added to the recirculating system to achieve the target values. The fuel temperature is then set to the target value via recirculation through the chiller; once achieved, the desired flow rate to the test unit is initiated while fuel continually recirculates to the conditioning tank to prevent water settling. The external temperature of the test unit is independently maintained via cooling with liquid nitrogen. Determination of ice formation and blockage of the test unit is made by monitoring the differential pressure across the unit and the overall fuel flow rate. Significant changes in these metrics are indicative of ice formation and blockage of the flow path.
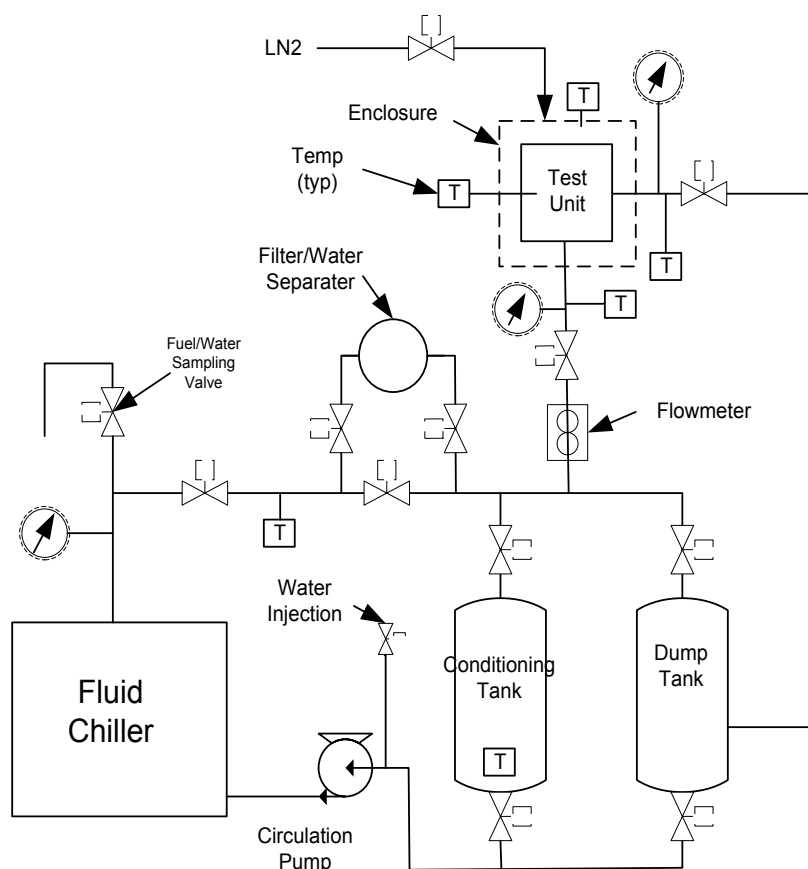

Figure 13. Process Flow Diagram of Fuel Conditioning and Test System for Component Level Testing at Parker Aerospace.

Testing was performed with the B-52 strainer housing using a fuel flow rate of 6 gallons/minute, which is similar to the required flow rate during aircraft cruise at altitude (Cash, 2004). It has been proposed that a worst flight condition for blockage due to icing may occur when a high flow rate is initiated following a sustained low flow rate at sub-freezing conditions (see ARP 1401B and AIR 790C). At low flow rates, the potential exists for ice accumulation in the fuel manifold upstream of the component. During transition to a high flow, the ice could be released and form a restriction which would result in reduced fuel flow. This has been identified as the most likely scenario for the cause of the accident to Boeing 777-236ER at London Heathrow Airport on 17 January, 2008 (AAIB Interim Report 2, 2009). During the current evaluation of a reduced FSII concentration, however, the potential implications of this scenario is not applicable. As previously stated, a primary goal was to determine a sufficient FSII concentration at which ice would not be present in the fuel. In addition, the test facility is designed to deliver all ice formed to the test component and prevent accumulation at other locations in the Fuel Conditioning System. Therefore, evaluation at a constant fuel flow rate is applicable.

Testing was performed while varying the total FSII and water contents and test temperature. Initially, the attempt was made to perform the testing similar to that prescribed in the SAE ARP and AIR. The first test was performed with FSII-free fuel with 288 ppm total water while passing half of the fuel volume through the component at test temperatures of -9°C (+15°F) and -40°C, respectively. Testing showed complete failures (significant pressure rise and loss of fuel flow) after approximately 25-30 minutes for the FSII-free testing at -9°C (+15°F), indicating that the test set-up was capable of reliably indicating failure due to icing. Visual inspection of the test filter showed significant ice accumulation with complete coverage of the filter element. Testing was then performed using 0.07% DiEGME with 288 ppm total water to represent the current FSII use level. This testing showed no decrease in measureable component fuel flow or increase in pressure differential. However, it was determined that with the presence of FSII, performing the test at -9°C (+15°F) (critical icing temperature) is not a relevant condition since even low concentrations and partitioning would prevent solidification under this condition (see Figure 4). Therefore, subsequent testing was performed at a single test temperature.

Several difficulties were encountered during the following FSII-efficacy testing with the B-52 fuel strainer. It was determined that the majority of these problems were a result of attempting to perform detailed quantitative evaluation of the effectiveness of varying FSII concentration on a large-scale using the ARP and AIR for standard icing evaluation. It was determined that the recommended methodologies for fuel conditioning and component testing for FSII-free evaluations can introduce experimental artifacts during FSII-efficacy testing. This resulted in several improvements to the testing methodology, which significantly improved the overall quality control and applicability of the testing and which were incorporated into the recently updated SAE 1401B. A detailed discussion on all studies performed, modifications to the test methodology and improvements will be provided in subsequent reporting; overall comments and primary test results are provided below.

During large-scale evaluation of a reduced FSII concentration, several experimental parameters were determined to be critical to control for quantitative evaluations to be performed. These parameters included:

- Precise Control of Total Water and FSII Concentration
- Sufficient Contacting Time for FSII Partitioning
- Testing at Single Condition with Entire Volume of Test Fuel

As previously noted, there is no established methodology for "FSII-evaluations" or a "FSII-performance" specification. Icing qualifications are typically performed without FSII in the fuel. The consequence of this is that solid ice is most likely present (and probably desired) in the fuel conditioning system during testing. A standard icing test will determine if a component can function properly with ice accumulation; slight variations (±10-20%) in the total water content will most likely not affect the final test results. However, a goal of the current program is to define a reduced FSII concentration where there will not be any solid formation in the fuel. Therefore, precise control of the total water and FSII content is vital for quantitative evaluations to be performed, especially when operating near the icing transitional regime for FSII/water mixtures. It was determined that the recommended practice of over-saturating the fuel with excess water at 80°F and filtering with a coalescer could allow excess water to exist in the fuel system which is not readily detected. In particular, if the fuel is at the saturation limit, it is not possible to determine if excess free water is present in the system. Therefore, a modification of the initial fuel conditioning was made to first chill the fuel to 35-40°F, remove free water by passing through the coalescer, and then heating the fuel to 80°F. Samples at the elevated temperature were then analyzed for the total water content. The benefit of this approach is that if the measured total water content is below the saturation limit at 80°F, all water in the fuel system should be dissolved and there is higher confidence in the total water content. High-precision analytical methods are required to verify total water and FSII content of the treated fuel due to the effect of potential inaccuracies while attempting to precisely condition a large-volume of fuel. Multiple sample analyses were performed during each stage of the fuel preparation, using high precision Gas Chromatography/Mass Spectrometry (GC/MS) and Karl-Fischer titration, to improve confidence in the measured total DiEGME and water concentrations. All sample analyses were performed at the AFRL/RQTF laboratory for improved quality control.

Due to the design of the fuel conditioning system, only a small portion of the fuel volume is actively chilled during the cool-down segment of the test. This can result in a significant temperature differential between fuel in the chiller as compared to that in the conditioning tank. As previously discussed (Section 3.2), the partitioning of FSII from the fuel to free water is highly dependent on temperature. In the event that the fuel (or portion of) is cooled more quickly than the FSII can partition, the potential exists that the freeze point of the existing water/FSII mixture will be exceeded and solidification will occur (see Figure 4), even though there is sufficient overall FSII in the tank to prevent freezing. Therefore, a modification to the method was made to cool-down the fuel using sequential temperature steps with equilibration time to allow for adequate contacting and to prevent undercooling and solidification. Within an aircraft wing tank, all exposed external surfaces and the integral wing structures (e.g., struts and ribs) participate in the fuel cooling process, resulting in a more homogeneous cooling of the fuel volume and reduced potential for ineffective FSII partitioning. A final modification to the test methodology was to pass the entire fuel volume through the Strainer at a single test condition. This was performed since once excess water has been added to the fuel, the overall fuel/FSII/water mixture will not be homogenous. Passing the entire fuel volume through the

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component will insure that the component is exposed to the entire volume of water during testing.

Several FSII-evaluation tests were performed using the modified test procedures. All tests were performed with a total water concentration of 125 ppm and FSII contents based on the minimum required levels from the preceding bench- and small-scale testing. A summary of the result from the testing is shown in Table 3. The first test was performed with a total water content of 125 ppm and 0.04% DiEGME at -40°C and showed no change in measurable fuel flow rate or increase in differential pressure across the filter, indicating no ice formation. The second test was performed with the same water content and temperature with 0.031% DiEGME; however, the target concentration was intended to be 0.035%. This test resulted in ice formation and a gradual increase in differential pressure/decrease in flow rate from 30-90 minutes of test duration. Inspection of the fuel strainer (see Figure 14) showed a substantial quantity of "Extremely Slushy Ice which is similar to that typically observed during testing at +15°F with a small amount of FSII". It should be noted that although there was substantial ice accumulation on the strainer, the fuel flow rate was still active (~3 gal/min at 75 minutes), potentially indicating that the system was near a transitional regime with respect to ice formation. Therefore, a supplemental test was performed with 0.041% FSII and 125 ppm total water at -44°C (-47°F). This test condition was chosen to provide a measure of reproducibility to the previous 0.040% test but at a slightly lower temperature. The -44°C temperature was chosen because this is the minimum allowable operating fuel temperature for most aircraft, since the majority of USAF aircraft T.O.s require that the measured Outside Air Temperature (OAT) (also referred to as the recovery or skin temperature) be no less than +3°C above the specification freeze point of the fuel on-board the aircraft (-47°C for JP-8). This test showed no change in measureable fuel flow, differential pressure measurement or ice formation upon visual inspection (see Figure 15). This is a very encouraging result in that no solid formation occurred with the 0.04% DiEGME with what is believed to be a "conservative" amount of total water.

Table 3. Results from B-52 Fuel Strainer FSII Testing at Parker Aerospace

DiEGME Concentration (vol%)	Water Content (ppm)	Test Condition	Result
0.040	125	-40°C	**Passed**
0.031	125	-40°C	**Failed; reduced flow maintained**
0.041	125	-44°C	**Passed**

The evaluation of the effectiveness of reduced FSII concentrations using the B-52 strainer housing showed that a substantially lower concentration, approximately 0.04% by volume, than required by the JP-8 specification can prevent solid formation and flow passage blockage to temperatures of the bulk fuel solidification. These results should be applicable to most USAF aircraft fuel systems, especially those which are equipped with anti-icing hardware or which have bulk fuel temperatures which do not approach the specification fuel limit. *The studies performed demonstrated that the transitional regime for icing with 125 ppm total water is most*

likely near 0.030% DiEGME, indicating that a level of 0.04% provides an additional margin of safety. The results from the large-scale testing are consistent with those from the other aspects of the overall program and previously reported by the U.S. Navy, and demonstrate the importance of fuel contacting and mixing during evaluation of a FSII.

Figure 14. B-52 Fuel Strainer with Accumulated Ice Following Testing with 125 ppm Total Water and 0.031% DiEGME at -40°C.

Figure 15. B-52 Fuel Strainer with no Visible Ice Accumulation Following Testing with 125 ppm Total Water and 0.041% DiEGME at -44°C

3.5 Impact of Reduced FSII Concentration on Frequency of Fuel Tank Topcoat Peeling
DiEGME has recently been implicated in the failure of integral Fuel Tank Topcoats, most
notably in the B-52 (Aliband et al., 2006; Marlowe and Green, 2007; Zabarnick et al., 2007;
Aliband et al., 2008). The B-52 topcoat layer is Boeing Material Specification (BMS) 10-39,
which serves as a physical barrier between the fuel and the aluminum substrate. This failure
process has been termed Fuel Tank Topcoat Peeling (FTTP) and can result in the exposure of the
aluminum substrate leading to corrosion and pitting of the metal surfaces and fasteners. In
addition, topcoat flakes that have lost adhesion can block fuel filters and screens resulting in loss
of fuel flow. Evidence suggests that FTTP occurs in the ullage space above the fuel level when
DiEGME selectively volatilizes relative to many of the compounds in JP-8 due to the higher
vapor pressure of DiEGME (Aliband et al., 2006). The DiEGME-rich vapor can condense on
ullage surfaces upon a sufficient temperature differential, resulting in a condensate with a much
higher DiEGME concentration than the base fuel promoting FTTP. If the DiEGME dose
concentration in the fuel is decreased, the potential exists for a reduction in the resulting
concentration of DiEGME both in the vapor phase and the condensate on the ullage surfaces.

Although the proposed mechanism for FTTP is plausible, the chemical and physical processes
which result in FTTP are not completely understood. More information is needed pertaining to
the required concentrations, temperatures, and time of exposure to induce FTTP. Extensive
efforts were performed to improve the understanding of the FTTP mechanism and implications
of a reduced FSII concentration in the fuel (Adams, 2009; Zabarnick et al., 2009; Zabarnick et
al., 2010); detailed overview and discussion of these efforts is provided in the pertinent
references. These efforts included exposure studies of both aged (e.g., acquired from a scrapped
Model-G B-52 from Boeing Wichita) and new topcoat panels to investigate the effect of
DiEGME concentration in fuel and water on the extent of absorption into the topcoat and
resulting effect on material integrity as rated by the pencil hardness of the coating. Several
studies were performed to investigate the relative volatility of DiEGME to JP-8 and to quantify
the resulting concentration of FSII in vapor condensates. A major accomplishment was the
development of a simulated fuel tank box which allowed for investigation of the effect of the fuel
and condensing surface temperatures, the fuel concentration of FSII and the exposure duration on
FTTP. It was possible to re-create topcoat failures in a controlled setting using the simulator
allowing for improved understanding of the controlling variables on FTTP. <u>For what are
believed to be representative conditions, it was found that DiEGME concentrations in the fuel
$\leq$ ~0.05% showed no reduction in topcoat integrity while a rapid decrease can occur at levels
> ~0.07%.</u> Therefore, a low FSII use concentration could reduce the occurrence of FTTP.
However, in the event that the procurement specification range increases the typical level of FSII
to significantly > 0.07% in the aircraft fuel tanks, the impact on the frequency of FTTP is
unknown. With the recent approval of the 0.040% FSII use concentration, a recommendation is
made to introduce the lowest possible concentration of FSII into the aircraft.

3.6 Investigation of Loss of FSII during Transport and Storage of JP-8

Although the affinity of DiEGME for free water is necessary to perform its anti-icing function, this provides a means through which FSII can be inadvertently extracted and lost during fuel storage and transport operations. Any contact between the fuel and free water originating from the environment or as a result of environmental changes represents a potential for FSII to be extracted from the fuel. This FSII is then lost from the system when the extract phase is removed during the routine draining of storage, transport and filtration vessel sumps. Therefore, the minimum procurement limit and range is specified to insure that sufficient FSII remains in the fuel to satisfy the minimum on-board use limit. The previous procurement range (0.10-0.15% by volume) was established based significantly on the anticipated losses in the procurement chain and allowable variability required during FSII addition (e.g., additive injector accuracy) in the 1980s. Recently, there have been significant technological improvements in fuel handling and storage and additive injector technology. Therefore, the potential implementation of a reduced use concentration should be accompanied by a determination of the required procurement range based on the current fuel distribution and storage systems and technologies. This is critical to maximize the beneficial economic and logistical aspects of a lower FSII concentration while insuring the required concentration is maintained at the aircraft.

An extensive survey study was undertaken by the Air Force Petroleum Agency (AFPET) to identify FSII losses during storage and transport of JP-8 (Shaeffer, 2007; Regoli, 2009). The specific approach employed collection of all available FSII concentration data from 39 world-wide USAF bases over the 12 month of calendar year 2007. The bases comprised a wide range of fuel delivery modes (e.g., pipeline, truck, barge) and environmental conditions. The overall methodology employed and interim results for this survey have been reported elsewhere (Shaeffer, 2007; Regoli, 2009). The extensive in-field survey showed that the majority of bases (97%) had *statistical losses of ≤ 0.02% FSII through the procurement chain*. Combined with the recommendation of a minimum FSII use limit of 0.04%, it is feasible for the *minimum procurement limit of FSII to be set to 0.06-0.07%*.

4. Summary and Recommendations

There is significant interest in determining the minimum use concentration of the FSII additive required in U.S. military aviation fuels to maintain safe and equivalent operability. A lower required concentration of FSII could render significant logistical and economic cost savings and potentially reduce undesirable material compatibility occurrences attributed to FSII. Though it is difficult to specify a use limit that is applicable for all platforms, the current efforts built on the historical data and understanding to determine this value. A base assumption was made that the FSII should provide protection to bulk temperatures as low as -47°C, which is the specification freeze point for JP-8. The B-52 was used as the basis for evaluation when a specific platform was required for testing since aircraft losses attributed to fuel system icing provided the initial motivation for FSII and the fuel system does not have any specific hardware to prevent ice formation or water accumulation.

Several factors from the present effort support the feasibility of a low use concentration while maintaining safe operation of aircraft. Estimations and in-field measurements of the total water content expected on aircraft indicate that very low total concentrations of water (< 120-130 ppm) should be encountered during standard operation. These expected levels are based on the assumption that the fuel system maintenance and housekeeping is performed per the Technical Order requirements. Partitioning measurements show that FSII readily migrates from the treated fuel into any free water present. The propensity and percentage of the migration increases with reduced temperature and concentration, which is favorable when implementing a lower concentration in the fuel. Small-scale icing studies using sections of actual fuel strainer filter elements from the B-52 and metal screens show that even with a high total water content (288 ppm), concentrations of DiEGME as low as 0.03% by volume can prevent ice formation even at the specification temperature limit of JP-8 (-47°C). This data is in agreement with previous extensive small-scale testing by the U.S. Navy. Component-level testing with a B-52 fuel strainer housing provided validation of the small-scale testing and an improved definition of the required minimum use limit. During the component testing, it was found that the transitional regime for icing with 125 ppm total water is most likely near 0.030% FSII. **Based on data and understanding from previous studies and the extensive efforts performed herein, the recommendation was made that the minimum use limit of FSII on USAF aircraft operating with JP-8 be reduced to a level of 0.04%, which should be capable of providing anti-icing efficacy for representative water levels at fuel temperatures to -47°C, with an additional margin of safety.** The results from the current component testing are consistent with those from other component evaluations previously reported by the U.S. Navy, and demonstrate the importance of fuel contacting and mixing during evaluation of a FSII. Biological growth studies indicated that even at this reduced FSII level in the base fuel, the resulting aqueous phase concentration should be sufficient to provide comparable performance to current FSII use and procurement levels. This lower concentration (0.04%) may reduce the frequency of Fuel Tank Topcoat Peeling occurrences. The implications of FSII-loss during fuel transfer and storage which were addressed in a separate effort by AFPET and showed the majority of USAF bases had statistical losses of ≤ 0.02% FSII through the procurement chain. Combined with the recommendation of a minimum FSII use limit of 0.04%, it is feasible for the minimum procurement limit of FSII to be set to 0.06-0.07%.

5. Acknowledgements

6. References

AAIB Interim Report 2, "Accident to Boeing 777-236ER, G-YMMM at London Heathrow Airport on 17 January 2008, released 12 March 2009.

Adams., R.K., "Determination of Fuel Tank Topcoat Material Compatibility with Diethylene Glycol Monomethyl Ether and Triethylene Glycol Monomethyl Ether," *M.S. Thesis-University of Dayton*, 2009.

Aliband, A., Lenz, D.W., DuPois, J., Alliston, K., Storhaug, V., Stevenson, L.E., Whitmer, T., Cash, R., Burns D. and Stevenson, W.T.K., "Epoxy Paint Failure in B-52 Fuel Tanks, Part I-Preliminary Development of a Model for the Process," *Progress in Organic Coatings*, 56, pp. 285-296, 2006.

Aliband, A., Lenz, D., Stevenson, L., Whitmer, T., Cash, R., Burns D. and Stevenson, W.T.K., "Epoxy Paint Failures in B-52 Fuel Tanks, Part 2 – Influence of DiEGME Concentration in the Fuel on the Failure Process," *Progress in Organic Coatings*, 63(1), pp. 139-147, 2008.

API 1581, "Specifications and Qualification Procedures for Aviation Jet Fuel Filter/Separators – 5th Edition," released 1 July 2002.

ASTM D1177, "Standard Test Method for Freezing Point of Aqueous Engine Coolants," released 1 April 2007.

ASTM D5006-03, "Standard Test Method for Measurement of Fuel System Icing Inhibitors (Ether Type) in Aviation Fuels," released 1 Dec 2003.

Balster, L., Vangsness, M.D., Bowen, L.L., Mueller, S.S., and Brown, L.M., "The Effect of DiEGME on Microbial Contamination of Jet Fuel: A Minimum Concentration Study," AFRL-RZ-WP-TR-2010-2002, 2010.

Cash R., *via personal correspondence*, 2004.

Cummings, J.R., "Performance Evaluation of Potential Fuel System Icing Inhibitors in Aviation Jet Fuel Using the U.S. Navy Aircraft Fuel System Icing Simulator," NAVAIRWARCENACDIVTRENTON-LR-PPE-97-3, 1997.

DeWitt M.J., Williams, T.F., Shafer, L., Striebich, R., Riehl, L., and Delaney, C., "Investigation of the Effectiveness of DiEGME to Suppress Solidification of Water in Aircraft Fuel Systems," *Proceed. 9th Int'l Conf. on Stab. and Hand. of Liq. Fuels*, 2005.

DeWitt, M.J., Williams, T., Shafer, L., Striebich, R., and Riehl, R., "Investigation of the Effectiveness of DiEGME to Suppress Solidification of Water in Aircraft Fuel Systems," AFRL-PR-WP-TR-2005-2167, 2005b.

DeWitt M.J., Zabarnick, S., Williams, T.F., West, Z., Shafer, L., Striebich, R., Breitfield, S., Delaney, C.L. and Phelps, D., "Determination of Minimum Required FSII Dosage for Use on USAF Aircraft," *Proceed. 10th Int'l Conf. on Stab. and Hand. of Liq. Fuels*, 2007.

DeWitt, M.J., Zabarnick, S., Shaeffer, S., Williams, T., West, Z., Shafer, L., Striebich, R., Breitfield, S., Adams, R., Cook, R., Delaney, C.L., and Phelps, D.K., "Determination of Minimum Required Fuel System Icing Inhibitor (FSII) Use and Procurement Limits for USAF Aircraft," *Proceed. 11th Int'l Conf. on Stab. and Hand. of Liq. Fuels*, 2009.

Federal Aviation Administration, "Use of Aircraft Fuel Anti-Icing Additives," Advisory Circular (AC) 20-29B, published 18 January 72.

Hill, G.C., Hill, E.C., and Anderson, S., "Investigation of the Anti-Microbial Characteristics of Di-Ethylene Glycol Mono Methyl Ether (DiEGME) in Relation to its Use Intermittently and at Sub-Lethal Concentrations," *Proceed. 9th Int'l Conf. on Stab. and Hand. of Liq. Fuels*, 2005.

Langer, G., "JP-4 Fuel System Icing," Armour Research Foundation of IIT, ARF 3165-3, 1960.

Marlowe, D.L. and Green, M.G., "Investigation into the Cause and Effects of Widespread Coating Failures and Corrosion on the Internal Surfaces of P-3 Orion Wing Integral Fuel Tanks," *Corrosion Reviews,* 25(5-6), pp. 533-544, 2007.

Martel, C. R., "Military Jet Fuels, 1944-1987," Air Force Wright Aeronautical Laboratories, AFWAL-TR-2062, 1987.

MIL-DTL-83133H with Amendment 1, "Detailed Specification, Turbine Fuel, Aviation, Kerosene Type, JP-8 (NATO F-34), NATO F-35, and JP-8+100 (NATO F-37)," released 14 September 2012.

MIL-F-17874B, "Fuel Systems: Aircraft Installation and Test of," released 20 August 1965.

Mushrush, G.W., Beal, E.J., Hardy, D.R., Hughes J.M., and Cummings, J.C., "Jet Fuel System Icing Inhibitors: Synthesis and Characterization," *Industrial & Engineering Chemistry Research*, 38, pp. 2497-2502, 1999.

NASA, http://exploration.grc.nasa.gov/education/rocket/atmos.html, 2007.

NAVAIR 00-80T-109, "Aircraft Refueling NATOPS Manual," released 15 June 2005.

Oreshenkov, A.V., "Accumulation of Water in Jet Fuels. Mathematical Modeling of the Process," *Chemistry and Technology of Fuels and Oils*," 40(5), pp. 320-325, 2004.

Regoli, V.M., "Loss of Fuel System Icing Inhibitor Additive During the Transportation and Storage of JP-8," AFPET-TR-14092009, 2009.

SAE ARP 1401A, "Aircraft Fuel System and Component Icing Test," released 1 December 1997.

SAE ARP 1401B, "Aircraft Fuel System and Component Icing Test," revised 1 June 2012.

SAE AIR 790C, "Considerations on Ice Formation in Aircraft Fuel Systems," released 1 August 2006.

Shaeffer, S., "Loss of Fuel System Icing Inhibitor Additive During Fuel Transport and Storage," *Proceed. 10th Int'l Conf. on Stab. and Hand. of Liq. Fuels*, 2007.

T.C.T.O. 1B-52-1878, "Deletion of Engine Fuel Heater System B-52A, B-52B, B-52C, B-52D, B-52E, and B-52F Series Aircraft," released 16 September 1968.

T.C.T.O. 1B-52H-606, "Deactivation of Fuel Heaters – B-52H," released 12 October 1962.
T.C.T.O. 1B-52H-663, "Deletion of Engine Fuel Heater System – B-52H Series Aircraft, released 15 February 1968.

T.C.T.O. 1B-52G-733, "Deletion of Engine Fuel Heater System B-52 Series Aircraft," released 1 March 1969.

T.O. 42B-1-1, "Quality Control of Fuels and Lubricants," released 13 August 2012.

Tyler, J.C., "Performance of Critical Navy Aircraft System Components at Low Temperatures," *Interim Report BFLRF No. 252*, Belvoir Fuels and Lubricants Research Facility (SwRI), 1988.

West, Z., Shafer, L., Striebich, R., Zabarnick, S., Delaney, C., Phelps, D., and DeWitt, M.J., "Equilibrium Partitioning of DiEGME Between Fuel and Aqueous Phases at Sub-Ambient Temperatures," *in preparation*, 2014.

Zabarnick, S., West, Z., DeWitt, M.J., Shafer, L., Striebich, R., Adams, R., Delaney, C.L., and Phelps, D., "Development of Alternative Fuel System Icing Inhibitor Additives That are Compatible with Aircraft Tank Topcoat Material," *Proceed. 10th Int'l Conf. on Stab. and Hand. of Liq. Fuels*, 2007.

Zabarnick, S., Adams, R., West, Z., DeWitt, M.J., Shafer, L., Striebich, R., Delaney, C.L., and Phelps, D.K., "Studies of the Compatibility of DiEGME and TriEGME Icing Inhibitor Additives with Aircraft Tank Topcoat Material," *Proceed. 11th Int'l Conf. on Stab. and Hand. of Liq. Fuels*, 2009.

Zabarnick, S., Adams, R., West, Z., DeWitt, M.J., Shafer, L., Striebich, R., Delaney, C.L., and Phelps, D., "Compatibility of DiEGME and TriEGME Fuel System Icing Inhibitor Additives with BMS 10-39 Aircraft Tank Topcoat Material," *Energy & Fuels*, 24, 2614-2627, 2010.